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FIELD TESTS WITH INERT GAS AND HIGH-EXPANSION FOAM

by

J.H. McGuire and K. Sumi

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PREFACE

The field tests described in this report followed from a meeting of various fire officials called to discuss the utilization of inert gas on a large scale for the extinguishment of fires in buildings. Evidence of a practical nature of the potential of the technique in buildings was required. An experimental high-expansion foam generator was also included in the apparatus taken to the site, primarily to note the behaviour of inert-gas high-expansion foam. In fact more attention was paid to experimenting with conventional (air) high-expansion foam because its performance proved so interesting. These tests were carried out at the Ontario Fire College at Gravenhurst, Ontario, in early May 1966, with the kind co-operation of the Ontario Fire Marshal.

The authors of this report are research officers in the Fire Research Section of the Division of Building Research.

Ottawa
January 1967

N.B. Hutcheon
Assistant Director

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by

J.H. McGuire and K. Sumi

With a view to increasing knowledge on the usefulness of inert gas and high expansion foam as extinguishing agents for building fires, the Ontario Fire Marshal was kind enough to make available for test purposes the fire test building of the Ontario Fire College at Gravenhurst. This building (see Figures 1 to 4) is a 3-storey structure which will withstand, without damage, exposure to intense fires within it.

Up to this time experiments with the NRC generators had been confined to an enclosed test area 40 ft cubed and a small wooden shed about 17 ft long, 7 ft wide, and 10 ft high. Although much had been learned by the use of these facilities, two important pieces of information had not been derived. The first, concerning the inert gas generator, related to the effect of high-level openings. This effect had been predicted theoretically, and the theory had to some extent been confirmed by experiment. The accuracy of the experimental information was poor, however, because of difficulty in assessing the area of the high-level openings in the 40 ft cubed "burn area".

The second subject on which further information was required concerned the mobility of high-expansion foam. The Gravenhurst test building included various doors and enclosed staircases and was thus very appropriate for an investigation of this feature.

This report is intended to be a record of the work carried out at Gravenhurst and the tests are reported in chronological sequence regardless of their technical merits.

TEST FACILITIES

The inert gas generator has been adequately described elsewhere (1, 2) and for present purposes it is sufficient to say that it has an output of approximately 3300 cu ft/min at a temperature of about 90°C with a constitution of about 68 per cent water vapour, 28 per cent nitrogen and 4 per cent carbon dioxide.

Details of the high expansion foam generator have been prepared for publication (3). A diluted foaming agent solution is sprayed on a regular pyramid-shaped net from a full cone nozzle. A vane axial fan is used to blow air through the wetted net to produce foam.

The foaming agent solution used was sodium lauryl sulphate with an active content of 0.4 per cent, plus butyl carbitol. The latter was a solvent used to reduce the problem of mixing sodium lauryl sulphate with water. This foaming agent, developed at the National Research Council (3), was used at Gravenhurst because exploratory experiments indicated it to be very promising for combined use with hot inert gas. The pyramid-shaped net was made of nylon material having a base of 29 in. and a slant length also of 29 in.

The test building was a 30 ft high, 10,000 cu ft, 3-storey concrete block structure with concrete block partitions and reinforced concrete floors. The plans of each floor are given in Figures 2, 3 and 4. Independent enclosed stairways from ground to second floor and from second to third floor provided an interesting condition for examining the mobility of foam. Access to the third floor, for example, involved passing through five doorways and up two flights of stairs.

Heavy steel shutters were available on every window but some had been very badly warped by previous test fires and these windows (visible in Figure 1) were closed with 1/4-in. plywood before any tests were carried out.

During the course of most of the tests the behaviour of the test fire was monitored by a chromel alumel thermocouple a few inches above the fuel.

The injection points for the inert gas and the high-expansion foam were always those indicated in Figure 2. During the combined use the inert gas generator was preconnected to the foam generator and the resulting foam was injected at the window marked "foam".

Oxygen measurements were made with an instrument of the magnetic susceptibility type, samples being withdrawn from the building by 3/8-in. copper and tygon tubing. The sampling rate was such that the results might include unreported errors of up to a minute.

Test No. 1: Inert Gas Generator

All the exterior openings, doors and windows were closed and all the interior doors were left open. On the second and third floors, cans of gasoline and cribs were located at the positions indicated in Figure 4. The cans were of the 20 oz domestic variety 3 1/4 in. in diameter and 4 1/2 in. high and were filled to within an inch of the top with gasoline. The crib construction is illustrated in Figure 5. Thermocouples were installed over the cribs. Oxygen analysis was made at the locations indicated in Figures 2 and 4 on the ground and top floors, at a height of approximately 2 ft above the floor.

Table I gives the more important of the observations made. The commencement of gas injection is taken as the origin of time.

After injection had been stopped, about 15 min elapsed before the opening of various doors and windows had created a tenable atmosphere in the test building. It was then found that the crib fires had been completely extinguished and smouldering suppressed and that the gasoline fires had also been extinguished without much of the fuel being consumed.

Test No. 2: Inert Gas Generator

Having demonstrated that the inert gas generator was behaving normally and that the layout of the building did not impede fairly rapid mixing of the interior atmosphere, an experiment was carried out to indicate the effect of high-level openings. As will be seen from Table II, the performance was so satisfactory that, during the course of the experiment, a low-level opening was also created. The high-level openings consisted of one side of each of the top windows on the east side, and the aggregate area was 11 sq ft. The test fire and measurement conditions were as for test No. 1.

The results are indicated in Table II. The remark "low-level opening established" relates to the opening of the ground floor, south side window (of area 11 sq ft).

On re-entering the building the fires were found to be as effectively extinguished as previously.

With a view to predicting the performance of inert gas in enclosures, a theoretical analysis was made, some years ago (2) of the effect of high-level openings. It is interesting to compare the results of Table II with the predictions. The latter relate to an enclosure in which air entry at a low level is unrestricted, thus maximizing the undesirable effect of high-level openings. It was shown that if a completely inert atmosphere were to be established in a building the maximum permissible high-level opening would be

$$A = 3.86 \times 10^{-3} \, v/h^{\frac{1}{2}}$$

where

v = generator output, cu ft/min

h = height, ft.

Substituting v = 3300 cu ft/min and h = 18 ft gives the result A = 3 sq ft. A later report (4) discusses the effect of excessive vents and indicates that where an equilibrium oxygen content of 13 to 14 per cent is established, as prevailed after the low-level opening was created during the course of test No. 2, the high-level openings are about four times the critical area. A predicted high-level vent area of 12 sq ft therefore results. A further correction is called for as the theoretical analysis relates to unrestricted low-level openings. Where the low- and high-level vent areas have the same area, the neutral plane will rise to nearer the middle of the building and hence the critical area will increase by something of the order $\sqrt{2}$. The final predicted value will, therefore, be approximately 17 sq ft which is encouragingly close to the nominal measured value of 11 sq ft. This latter figure, of course, does not include the leakage around the roof trap, the windows other than the two in question and through the concrete blocks themselves. Figure 6 shows the inert gas (which has a high water-vapour content) flowing freely from the two open third-storey windows five min after injection had commenced.

Test No. 3: Inert Gas Generator

It had been intended to investigate the ability of the generator to extinguish a fire in a closed room, injection being elsewhere in the building. With this in mind, all exterior doors and windows were closed, together with the door to the third storey. It was later discovered, however, that a 16 in. square opening in the floor had been left uncovered. The test fire utilized the previous design of crib, and the results of the test are given in Table III.

When the building was re-entered both fires were found to be effectively extinguished, and smouldering had been suppressed.

Test No. 4: Inert Gas Generator

Test No. 4 was carried out to the specification of Fire

College officials who wished to have it demonstrated that the magnitude of the fire would not noticeably affect the efficacy of the technique. Two very large cribs about 4 ft cubed were located on the ground floor and were doused with fuel oil to give a rapidly developing fire. Unfortunately, the supposed fuel oil on one crib was largely water and this crib did not ignite satisfactorily. The other crib did, however, and for a period of nearly 4 min it was allowed to burn vigorously, both ground-floor doors and the roof vent being opened to give adequate ventilation.

When injection was commenced at one of the ground-floor windows on the east side, the roof vent and the doors were closed. The generator shut-down reported in Table IV was due to the failure on the part of the operator to open a manual valve in the liquid propane line. This omission was remedied, the propane vapourizer relit and the generator restarted in approximately 1 1/2 min. The oxygen concentration measurements reported in Table IV relate to the second storey and the sampling tube was about 2 ft 6 in. above the floor, some 6 in. higher than on previous occasions.

On re-entry of the building the cribs appeared to be completely inert and smouldering suppressed.

Test No. 5: Inert Gas Generator

For test No. 5 the conditions intended to be set for test No. 3 were established. All exterior doors and windows were closed, together with the door to the third storey, which did not fit as well as the average door in a building. The gap at floor level was almost an inch and elsewhere gaps of up to 1/4 in. existed. On this occasion a 1 ft square gasoline fire was used (in the same location on the third storey).

Shortly after the fire was extinguished a control experiment was conducted, the 1 ft square gasoline fire being allowed to burn without any attempt at extinguishment. The results of both experiments are recorded in Table V.

A highly simplified analysis of the results of test No. 5, made on almost precisely the same basis as for test No. 2, does not immediately yield satisfactory predictions. Thus, if an opening to the atmosphere of area 0.25 sq ft is at a height of 8 ft above the neutral pressure plane, a flow rate of about 230 cu ft/min will be established. If the above is taken to represent the conditions around the door to the third storey, which had a volume of approximately 2600 cu ft, then one would predict that one volume of inert gas would have penetrated the third storey within 11 min. The oxygen readings show that this was not the case, and the probable interpretation is that continuous temperature rise in the room was providing sufficient back pressure to reduce greatly the flow of inert gas into the room.

Further analysis of the prevailing conditions is of little interest as, in practice, a wide range of rates of temperature rise could be encountered.

Test No. 6: Foam

The ability of foam to migrate up the stairways and fill the ground and second floors was investigated. The foaming agent solution was sprayed at a rate of about 29 U.S. gpm and the air flow was maintained at about 3400 cfm. These conditions were also used for tests Nos. 7, 8 and 9. Both exterior doors and windows on the ground and second floors were closed. All interior doors, the roof vent and some third-floor windows were left open. The ground floor (including the first stairway) was filled with foam in 1 min 25 sec. The second floor was filled in 2 min, 5 sec.

The rate of filling the ground floor was about 2900 cfm, indicating the efficiency of converting air to the gaseous component of foam to be about 90 per cent. The rate of filling the second floor was about 1900 cfm indicating an efficiency of about 60 per cent. The over-all rate for both floors was 2300 cfm, indicating an efficiency of 70 per cent. The relatively high reduction in the rate of filling the second floor is to be expected because of the breakdown of foam as it is forced through the doorways and up stairways, and of losses of foam through cracks at windows and doors of ground and second floors.

Test No. 7: Foam

The migration of foam through 16 in. square openings was investigated. Two such openings were available from the ground floor to the second floor as shown in Figure 3, and two more were available from the second floor to the third floor, directly about the first two openings (Figure 4).

Both exterior doors, interior doors to the stairways and windows were closed. The roof vent was left open. The time at which foam started coming through each of the floor openings and the roof vent was recorded and reported in Table VI.

Floor openings a and b are on the second floor and c and d are on the third floor. Openings a and c are near the corner of the building where the foam was introduced. It was assumed that the ground floor was filled when foam started coming through the second opening b, and the second floor when foam started coming through opening d. On this basis the rate of filling the ground floor was determined to be about 2600 cfm, and of filling the second floor about 1800 cfm. These values are very close to those found for migration of foam up stairways (test No. 6). The rate of filling the third floor was found to be about 1040 cfm, and the time taken to fill the building was 5 to 6 min.

Test No. 8: Foam

Exploratory experiments conducted at Ottawa using a room 40 ft cubed indicated that a flammable liquid fire is much more difficult to extinguish with high-expansion foam than is a wood crib fire. Part of the difference was associated with the high ceiling. When a panel simulating a ceiling was positioned at a lower level, extinguishment of flammable liquid fire was not as difficult.

For the first extinguishment test with foam, in the current series, a 2- by 2-ft gasoline tank fire was selected. The tank, containing 1 in. of gasoline floating on 2 in. of water, was positioned on the third floor between the roof vent and the nearest window on the north side of the building. Exterior doors, windows and floor openings were all closed and all interior doors were left open so foam would have to travel up the stairways as in test No. 6.

Fire was extinguished 4 min 40 sec after start of foam injection as indicated by a thermocouple located just above the tank. Figure 7 shows foam coming out of the roof vent shortly after the fire was extinguished.

Test No. 9: Foam

An extinguishment test involving two large wood crib fires was carried out. The cribs were each 4 ft cubed, stuffed with paper and soaked with fuel oil; both cribs were located in the west room of the ground floor. A thermocouple was located above the wood crib distant from the foam generating net. The sampling tube for oxygen analysis was on the second floor at the position shown in Figure 3 about 30 in. from the floor. The results of this test are given in Table VII.

Test No. 10: Foam

Conditions similar to those for test No. 5 were established to determine if sufficient amount of foam would migrate through door cracks to extinguish fire. A 1- by 1-ft tank containing gasoline floating on water was positioned in a location similar to that for test No. 8. All exterior doors and windows and the third-floor door from the stairway were closed. The roof vent was left open. The results are given in Table VIII.

The rate of filling the ground floor with foam was 2000 cfm and the second floor was 1600 cfm for this test. Foam encountered considerable resistance at the closed door of the third-floor stairway. The gap at the floor level of almost one in. and gaps of up to 1/4 in. elsewhere provided sufficient openings, however, for some of the foam to enter the room at a slow rate to extinguish the fire.

Test No. 11: Combined Operation

There are practical applications for high-expansion foam in which the gaseous phase has an oxygen content lower than that of air. Rasbash (5) in the U.K., has shown that foams using a gas with an oxygen content of 16 to 17 per cent are much more effective in extinguishing flammable liquid fires than is air foam.

Another application of such foam is in fighting fires in large warehouses with high-piled stock or flammable roofing. It is not usually convenient to deliver foam from one appliance to a building at a rate exceeding about 10^5 cu ft/min and hence the complete filling of very large buildings might, on occasion, take 10 to 30 min. During this period it is desirable that flaming in the roof region be suppressed, and using an inert gas as the gaseous phase of the high-expansion foam will often achieve this. During the generation of high-expansion foam about 20 to 40 per cent of the gaseous component is usually not utilized, and where it has a low oxygen content it can be performing a useful function rather than supporting combustion as would air.

Generators of the types developed by the National Research Council and the Joint Fire Research Organization in the U.K. deliver gas at a temperature near that of boiling water, and exploratory tests conducted at Ottawa indicated that when the temperature of the gas is high the film stability of a foam is reduced and the drainage rate increased. To allow variation of gas temperature, provision was made for mixing air with inert gas. The foaming agent solution used in this combined operation was one that yielded promising results in exploratory experiments, as stated earlier.

Both exterior doors and all windows of the test building were closed for the combined operation; all interior doors and the roof vent were left open. In the first attempt to produce inert gas foam, about 1500 cfm of air was mixed with inert gas. The temperature of the combined mixture was 78°C. This temperature was used to estimate the oxygen concentration of the gaseous medium in the foam and the flow rate of inert gas by a method described elsewhere (6). The oxygen concentration of the gaseous mixture was found to be <8 per cent, and the flow rate of inert gas was about 3000 cfm.

Foam started coming out of the roof vent at about 3 min 45 sec after the start of foam injection. The rate of filling the building was estimated by assuming that, when foam started escaping from the roof vent, the first two floors were filled with foam but the third floor was not completely filled. The rate of filling the building was found to be between 2200 and 3100 cfm, indicating efficiencies of 50 to 70 per cent. The latter values are quite close to the efficiencies obtained in tests on high-expansion air foam. Therefore, foam production under these conditions could be considered satisfactory.

The air flow rate was next reduced to almost zero, providing just enough pressure to prevent inert gas passing through the vane axial fan of the foam generator in the reverse direction. The temperature of the gaseous mixture was about 85°C, producing a mixture with an oxygen concentration of <4 per cent. Foam production rate still appeared satisfactory as indicated by the movement of foam out of the roof vent.

CONCLUSIONS

(a) Inert Gas Generator

The equilibrium conditions established during the tests were predictable by an application of the elementary laws governing the flow of gases in a building. The complexity of the building did not invalidate the simple theory relating to high-level losses.

The time to establish equilibrium conditions, or to give some substantial degree of mixing, appeared to be at least 10 min, which is approximately three times the value of the time constant. Extinguishment times were reassuringly short, regardless of the relative locations of the fire and the point of injection.

(b) High-Expansion Foam

The relative ease of mobility of foam was demonstrated by tests in which foam was forced up stairways, through floor openings and around closed doors.

The test results further suggest that the migration of foam in any given building can be predicted by appealing to very simple theory, when the system is known as to geometry, volumes, openings and so on.

The fact that the foam satisfactorily flowed through five doorways and up two flights of stairs indicates that, as a first approximation, viscous drag may be neglected. The pressure head created by a substantial height of foam may also be neglected in most circumstances in comparison to the pressure which can be created by the foam generator. One can then say simply that the rates of flow by various paths will be proportional to the areas of the openings.

Thus, if faced with the arrangement illustrated in Figure 8, one would predict that after compartment No. 1 was nearly filled, the flow rates V_2 into compartment No. 2 and V_{loss} out of areas A_1 and A_2 would be:

$$V_2 = \frac{A_3 V}{A_1 + A_2 + A_3}$$

$$V_{loss} = \frac{(A_1 + A_2) V}{A_1 + A_2 + A_3} .$$

After compartment No. 2 was nearly filled, one might adopt the same approach concerning the flow into compartment No. 3 but this would involve two types of error. First, the flow impedances of the areas A_4 and A_5 would influence V_2 after compartment No. 2 filled and secondly, nonlinearities would now become effective as flow velocities though the various openings would no longer be the same. In the first part of the problem the flow velocities through A_1, A_2 and A_3 were the same.

This second feature can probably be ignored and the first can be accounted for by analogy with electrical networks. The predicted flow V_3 through area A_5 would be given by

$$V_3 = \frac{A_5 V_2'}{A_4 + A_5}$$

where

$$V_2' = \frac{A_3' V}{A_3' + A_4 + A_5}$$

$$A_3' = \frac{A_3 (A_4 + A_5)}{A_3 + A_4 + A_5}$$

A user could rapidly become familiar with the solutions to problems of this nature and hence could predict the likelihood of foam extinguishing a fire in any given circumstances. The time of extinguishment would, of course, also be predicted, provided that in all such cases the geometrical configuration of the system, i.e. volumes, doorways, areas of openings and so on, is known!

(c) Combined Operation

Inert gas foam having a low oxygen concentration, say 4 per cent, could be produced for possible use against difficult fires. The selection of foaming agent appears to be very important for such an operation because the gaseous mixture could be as high as 85°C. An agent developed at the National Research Council (4), sodium lauryl sulphate plus butyl carbitol or other suitable solvent, was found to yield satisfactory results on foam generation.

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* * * * * *

TABLE I

Test No. 1

Time (min)	O_2 (%)		Temp. (°F)		Remarks
	Top Floor	Ground Floor	Top Floor	2nd Floor	
-6					Fires lit.
-3			1400	1200	
0					Injection commenced.
2	18				
3			<300	<300	Both crib fires out.
5		8.5			
7		8			
9	12		100	100	
11	10				Injection stopped.

TABLE II

Test No. 2

Time (min)	O_2 (%)		Temp. (°F)		Remarks
	Top Floor	Ground Floor	Top Floor	2nd Floor	
-4					Fires lit.
-2			900	1200	
0					Injection commenced.
3	18.5		500		
4	17		200	250	
5	15		150		
6	13.5		150		
7	12.5				
8	12				
9	11.5				
10	11.2				
11	11.2				
12	11.2				
14		9.5			
16	12				Low-level opening established.
17	12				
18	12.3				
19	12.8				
20	13.5				
21	13.5				
22	13.6				
23		12.5			
24		13			
25		12.8			
26		12.8			

TABLE III

Test No. 3

Time (min)	O_2(%)	Temp. (°F)	Remarks
-4			Crib lit.
0			Injection started.
2	19.6	1300	
3	19.5	1040	
4	19.2	740	
5	18.2	520	
6	16.5	350	Fire probably out.
7	15.6	220	
8	15.0	160	
9	14.5	140	
10	14.2	120	
11	13.5	120	
12	13.3	120	
13	13.1	120	
14	12.8		
15	12.5		
16	12.5		

TABLE IV

Test No. 4

Time (min)	O_2 (%)	Temp. (°F)	Remarks
-3.5	19.5*	750	Crib lit.
-2.5	19.5*	250	*Probably gas left in sampling lines from previous experiment.
-2		1000	
-1.5	19.5	720	
-0.5	19.5	700	
0			Injection started.
1			Generator shut down.
1.5	18	380	
2.5	18	280	Restart.
3			Probably extinguished.
3.5	18	200	
4.5	17.6	180	
5.5	17	180	
6.5	16.5		
7.5	16.2		
8.5	15.7		
9.5	14.5		
10.5	12.5		
11.5	11.5		

TABLE V

Test No. 5

Time	Main Experiment			Remarks	Control Experiment
	O_2 Second storey (%)	O_2 Third storey (%)	Temp. (°F)		O_2 Third storey (%)
1	19.5		300		
2	19.5		350		
3	19.5		560		
4	17.5		570		
5	16.4		600		19.6
6	13.8		620		19.5
7	12.0		600		
8		18.5	620		19.2
9		17.8	600		
10		17.0	600		19
11		16.0	600		
12		15.4	580		18.8
13		14.2	580		
14		13.7	500		
15		12.8	280	Fire presumably out	18.6
16		12.5	280		
17					18.5
18		11.4			
19					18.5
21					18.3
23					18.3
25					18.2

TABLE VI

Test No. 7

Opening	Time
a	1 min 0 sec
b	1 min 25 sec
c	3 min 0 sec
d	3 min 25 sec
Roof vent	5 min 39 sec

TABLE VII

Test No. 9

Time (min)	O_2 (%)	Temp. (°F)	Remarks
-3	--	--	Cribs ignited. Both doors open.
-2	--	700	
-1	19.5	1100	
0	18.3	900	Foam injection started. North door closed
1	17.0	900	
2	16.3	750	
3	16.2	160	Fires extinguished.
3.5	--	--	South door closed.
4	16.5	150	
5	17.0	150	

TABLE VIII

Test No. 10

Time		Remarks
min	sec	
0	0	Foam injection started.
2	7	Foam reached landing on second floor.
4	40	Foam reached landing on third floor.
10	0	Fire started.
14	50	Fire extinguished.

Figure 1 Over-all views of test building.

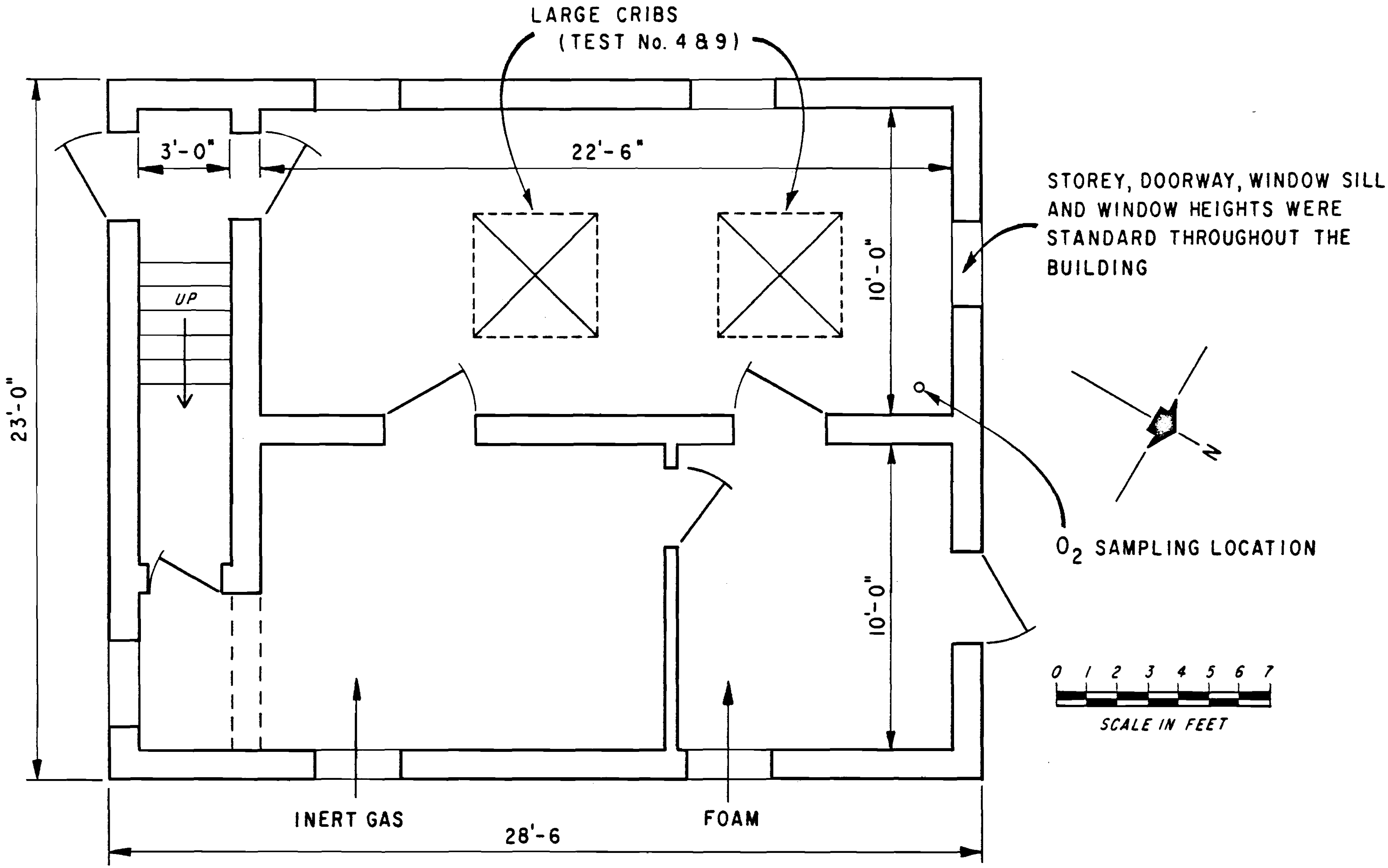

FIGURE 2 GROUND FLOOR PLAN, FIRE TEST BUILDING GRAVENHURST

BR 3754-1

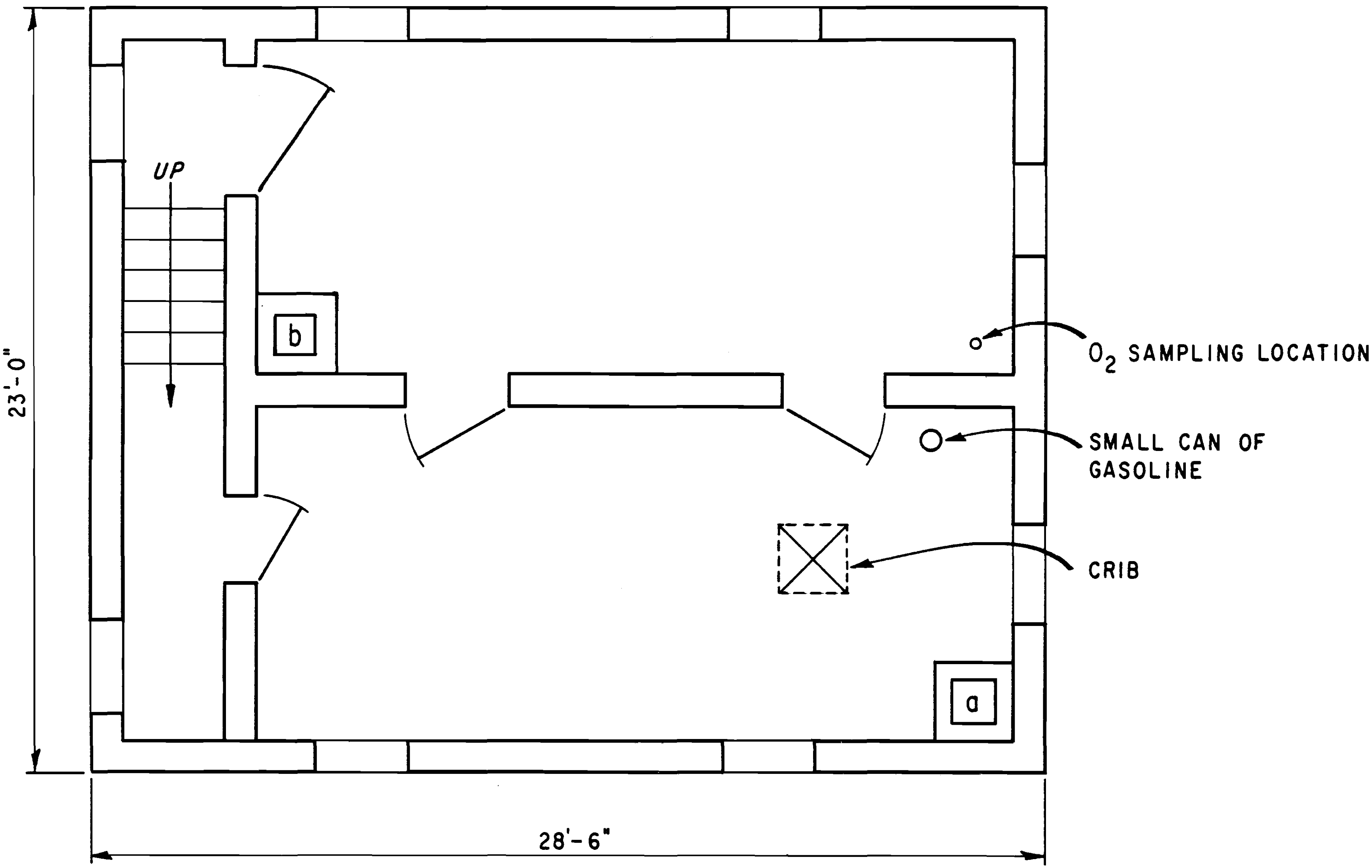

FIGURE 3 SECOND FLOOR PLAN, FIRE TEST BUILDING GRAVENHURST

BR 3754-2

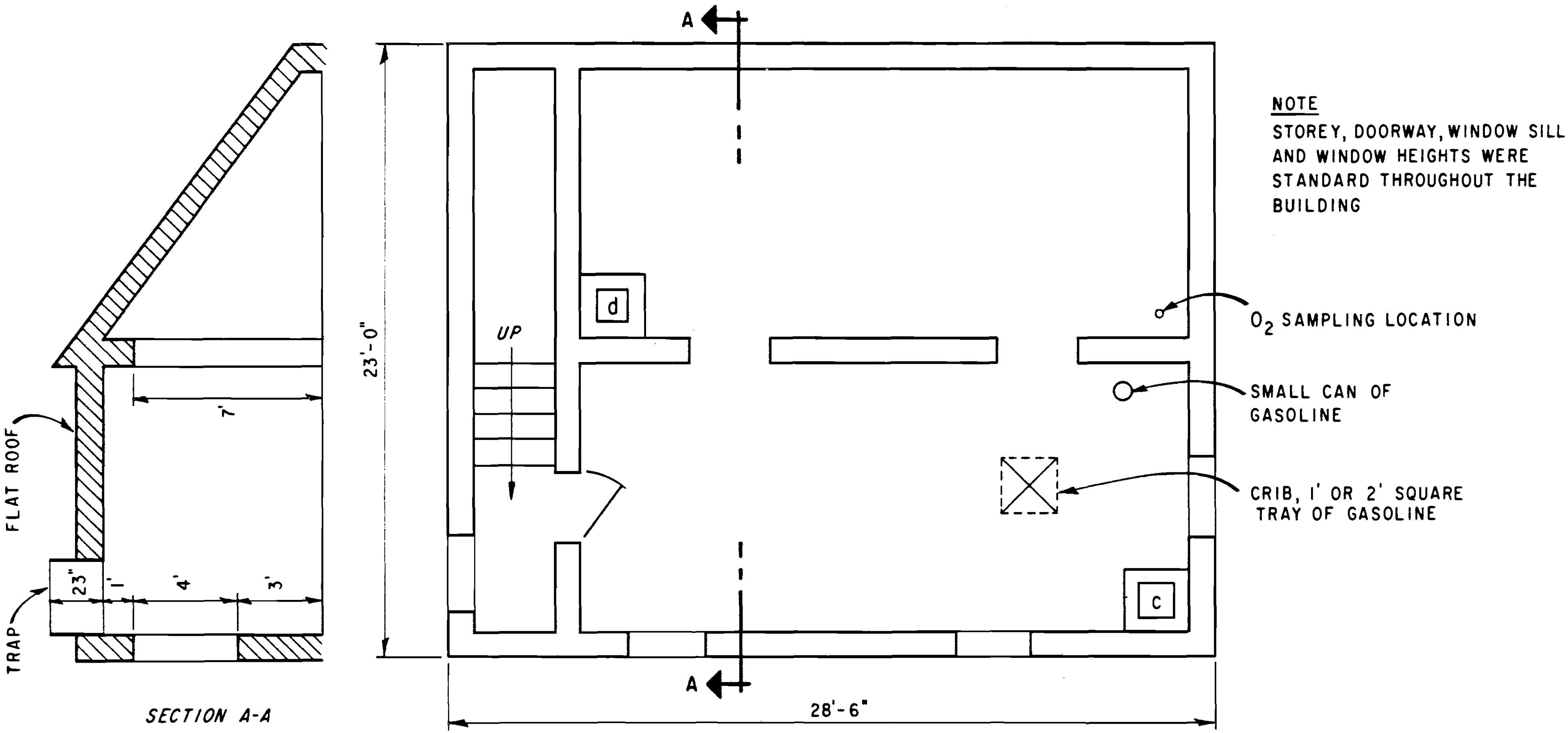

FIGURE 4 THIRD FLOOR PLAN, FIRE TEST BUILDING GRAVENHURST

BR 3754-3

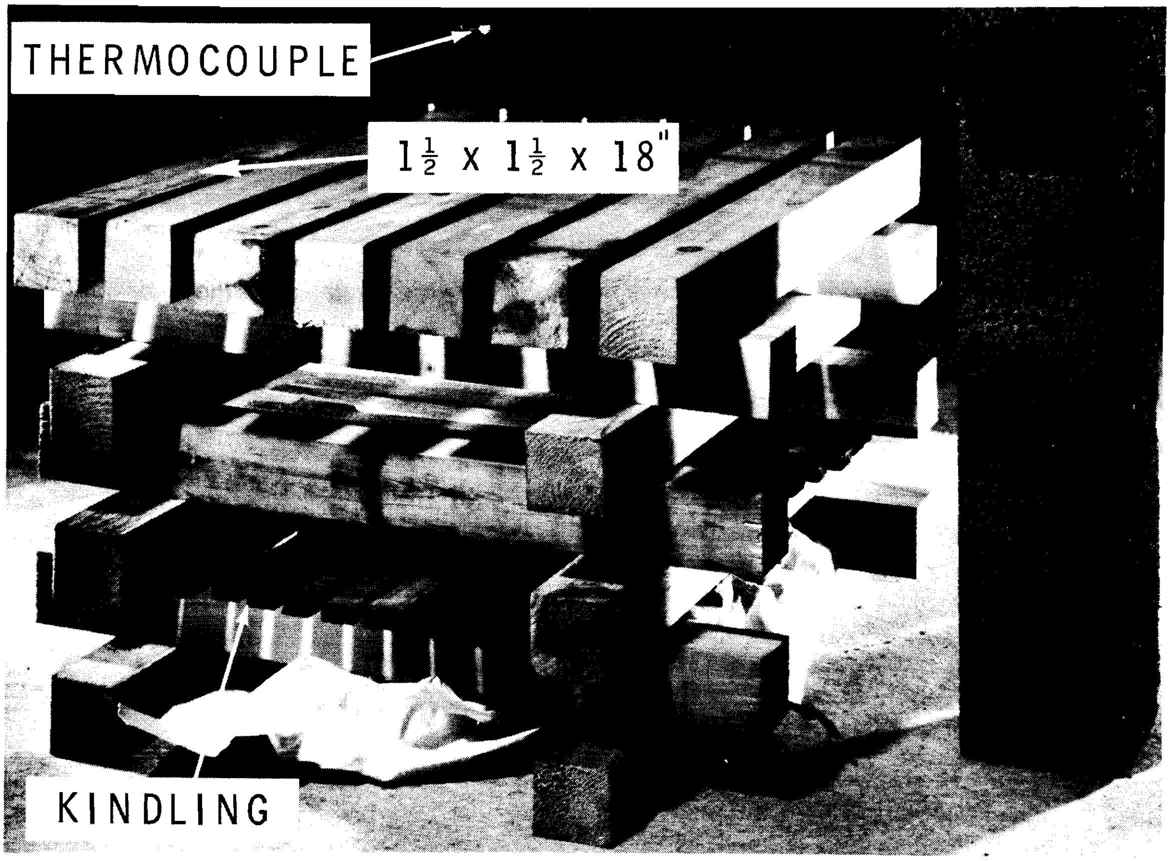

FIGURE 5 DESIGN OF SMALL CRIB

BR 3754-5

Figure 6 High-level loss of inert gas.

Figure 7   Foam issuing from roof vent.

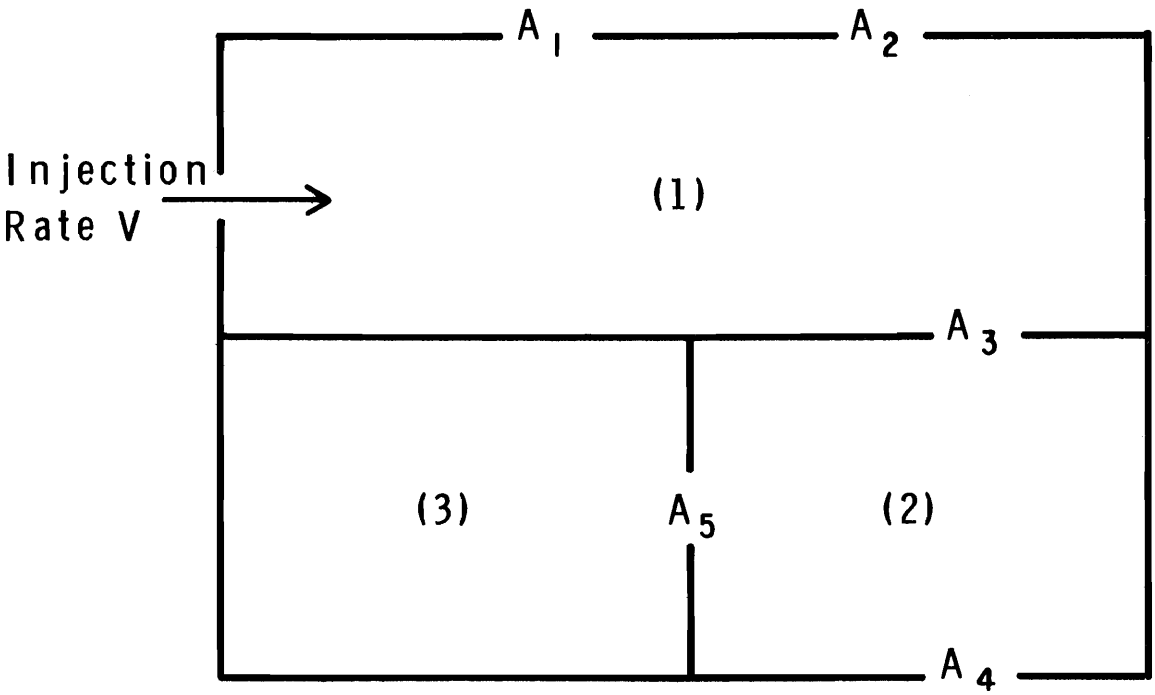

FIGURE 8 FOAM FLOW MODEL

BR 3754-4