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AN EXPERIMENTAL INERT GAS GENERATOR

by

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PREFACE

The many difficulties associated with the fighting of deep-seated building fires by conventional methods has led to a consideration of possible alternative approaches. One of these, the use of inert gas on a massive scale has received attention at the British Joint Fire Research Organization in the U. K., and is of much interest also to the Fire Section of the Division. Some discussion of the possibilities and requirements are now presented, together with a review of the work that has been carried out to convert a commercially available gas burner into a small-scale apparatus suitable for further exploration of the method.

The author, a physicist, is a research officer with the Fire Section concerned with the physical characteristics of fires in buildings.

Ottawa
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Building fires can be readily extinguished by conventional techniques, but only when it is possible to bring hose jets or fog nozzles to bear on a substantial proportion of the heated solid surfaces giving rise to the volatiles actually involved in the combustion process. Unfortunately, this latter condition can not always be met and on these occasions the best that fire fighters can do is to confine the fire to one building or compartment and to ensure that it does not spread to adjacent property.

In Great Britain and North America in particular, two alternative fire-fighting techniques are being considered and each shows some promise for certain classes of fire-fighting problems. One approach, which will not be considered in any detail here, is the use of high expansion foam which was originally developed in Great Britain to combat fires in mine roadways. Massive scale high expansion foam generators are now being marketed in the U.S.A. and it is hoped that the flow properties of the foam will allow the extinguishment of fires in relatively inaccessible parts of a building.

The approach that is the main concern of this report is the massive use of inert gas which was first conceived in a practical manner by the British Joint Fire Research Organization within the last decade. In order to assess the application of this technique a number of factors require consideration and these will now be discussed individually.

Permissible Oxygen Content of Inert Gas

When the oxygen concentration in an atmosphere is progressively reduced, the upper and lower flammability limits of combustible gases and vapours come closer together and finally meet (1, 2). In most cases this meeting point is at an oxygen concentration (of the atmosphere prior to the addition of the flammable gas) of more than 12 per cent. There are startling exceptions, however, such as hydrogen and carbon monoxide, for which the values are approximately 5 and 7 per cent respectively, but it is not likely that these gases will be greatly involved in building fires. The nature of the other gases constituting the atmosphere can also modify the flammability limits, but as the effect will almost invariably favour the use of inert gas as an extinguishing agent it is justifiable to ignore it. In general, therefore, if the oxygen concentration of the atmosphere in a burning building is reduced below about 12 per cent, flaming combustion will cease.

A fire fighter might ask that an inert gas should not merely suppress flaming combustion but should also suppress smouldering so that there is no likelihood of the fire rekindling when the oxygen content of the atmosphere returns to its normal level. Work reported by the British Joint Fire Research Organization (3) indicates that smouldering of cork dust and mixed hardwood sawdust will not continue in atmospheres with oxygen concentrations of about 9 and $12\frac{1}{2}$ per cent respectively at ambient temperature. At higher atmospheric temperatures smouldering or some other exothermic process can take place at lower oxygen concentrations. With all the techniques to be discussed in this report, however, the atmospheric temperature in a building will be reduced to below 300°F after injection has been continued for some time. J.R. Jutras (4) finds that at a temperature of 450°F smouldering is not readily sustained in wood sawdust at oxygen concentrations of less than 9.5 per cent.

The above considerations form the basis for the inert gas approach to the extinguishment of building fires, to be discussed in this report.

Required Rate of Generation

The rate of generation of the gas must be sufficient to meet two requirements. Firstly, the equilibrium conditions that will be established must be satisfactory, and secondly the time taken to attain equilibrium conditions must be reasonably low since it will correspond, approximately, to the time at which a fireman would describe the fire as "under control."

The existence of the first requirement allows simplification of the calculation of the time to attain equilibrium which will result from one of two mechanisms. The injection process might correspond to the filling of a bucket with water (or precisely the inverse) in which case equilibrium will be established when one volume of the gas is injected into the enclosure. At the other extreme, if perfect mixing occurred, the behaviour would be as shown in Table I which has been derived from Equation 3 of Appendix A. In this case equilibrium can be considered to be virtually established when three volumes of gas have been injected. For the purpose of this report an estimation of this time to a greater accuracy is not called for.

In general, failure to establish satisfactory equilibrium conditions in the fire compartment will result from density differences between the gases within the building and the air outside. To derive the most stringent injection requirements it is wise to consider the phenomenon to be exactly analogous to the filling of a leaky bucket with water (or precisely the inverse if the density of the injected gases is lower than that of air). The relevant variables are related by Equation 5 (Appendix B) and as the density of the injected gas is involved the expression must be evaluated separately for each gas considered.

Required Delivery Pressure

As a matter of convenience gases are often stored at high pressure and this fact, together with the development in Great Britain of a massive inert gas generator based on an aircraft gas turbine engine, has led some lay circles to assume that appreciable pressures are required for rapid delivery. This assumption is far from the truth and in fact prevailing pressures will usually be of the order of inches of water. The largest inert gas generator in existence (the British "jet engine" generator) has an output of about 40,000 cfm and such an output could be conveniently conducted through a 3-ft diameter duct at a velocity of 90 ft/sec (60 mph). The velocity head under these conditions, depending on the nature and temperature of the gases, would correspond to between 1 and 2 in. of water and the pressure drop over a 100-ft length of duct would be less than 10 in. of water.

Sources of Inert Gas

The ideal choice of inert gas would be one that, at the appropriate temperature, had the same density as air at ambient temperature. In this case there would be no gaseous losses of the type discussed in a previous paragraph by analogy with the filling of a leaky bucket. Carbon dioxide appears to be a very suitable choice from this point of view for its molecular weight is 44 compared to a value of 29 which is approximately the mean molecular weight of air. At a temperature of 140°C CO_2 will thus have the same density as air at 0°C.

If CO_2 were to be used on a building of dimensions 50 by 100 by 40 ft high, the quantity required, in the first instance, would be something of the order of the volume of the building, 200,000 cu ft. Its weight would be about 10 tons and, if transported in the 4 ft by 9 in. diameter size of cylinder, the cylinders would account for another 10 tons or so. The cost of the CO_2 would probably be of the order of $2,000 so that the demerits of the technique are probably mainly associated with cost and delivery.

Nitrogen is another gas that is worth considering for fire-fighting applications. In this case the molecular weight approximates to the mean molecular weight of air and hence nitrogen could be more readily retained in a building than could CO_2 as the building cooled down. As cooling might involve some substantial period of time the composite use of CO_2 and nitrogen would be theoretically desirable. In the first instance CO_2 would be injected and as the building cooled down nitrogen would be used. The principal demerit of nitrogen would be that its cost is many times greater than that of CO_2.

Without going into further detail on the application of stored commercial gases it will be appreciated that cost is an important factor and alternative generating techniques are worth investigating with a view to producing an appropriate gas at a lower cost.

Generation of Inert Gas by Combustion

For many years equipment has existed in which the oxygen content of the output has been substantially reduced by burning any convenient fuel and it has proven very effective in combatting fires in ships' holds (6).

The output from the combustion chamber of such a generator is, of course, not immediately suitable for use because of its high temperature and it is customary to cool it with water. This can be achieved either by a heat exchanger, allowing the water (or steam) to run to waste or alternatively by vapourizing water in the output. The latter technique has the advantage that it initially augments the gas supply, but it also has the disadvantage that the mean density of the output will be reduced thus giving rise to greater losses from high level openings as discussed earlier.

The output of the combustion chamber will be largely nitrogen which has a molecular weight of 28, approximating closely to the mean molecular weight of air, about 29. Water vapour on the other hand has a molecular weight of 18. The volume of water vapour generated in lowering the temperature to about 100°C will in general be of the same order as the output so that the mean molecular weight will drop to about 23. The failure to reduce the temperature to near ambient will also influence density to an even greater extent.

For these and other reasons it has been customary to cool the combustion chamber exhaust gases with heat exchanges and to present an output which consists mainly of nitrogen together with some miscellaneous products of combustion such as CO_2 and water.

Until recently the greatest output from a generator of this type has been of the order of 600 cu ft per min and by both the criteria discussed in the section "Required Rate of Generation" this is quite low. Thus if a compartment in which a fire is occurring has a volume of 100,000 cu ft, over 3 hours will elapse before one volume of gas has been injected. If the height of the compartment is 20 ft and the mean gas temperature is 100°C, the maximum permissible high level opening (from Equation 5, Appendix B) will be less than 1 sq ft.

Where the compartment concerned is the hold of a ship, battening down can meet the second requirement and the long-time scale is tolerable on the grounds that no other fire-fighting technique is likely to be successful.

For wider application much greater outputs are desirable, but this has been difficult to achieve owing to a lack of readily transportable high output combustion devices. If, as in a previous example, we consider a building 50 by 100 by 40 ft high, the discussion given earlier in this report will give the conclusion that the injection rate should be of the order of 40,000 cu ft /min. Delivery will thus be at the rate of 1 volume every 5 min and, neglecting losses, the oxygen concentration generally should be well down within 15 min which would appear to be an appropriate order of time. Subject to some variation, depending on the temperature and the nature of the output gas, Equation 5 (Appendix B) indicates that the maximum permissible high level opening in a 40-ft high building will be of the order of 25 sq ft. It would probably be unwise to design a machine intended for wide application which required high level openings in buildings to be substantially lower than this value.

The order of heat generation of a machine with an output of 40,000 cu ft/min is 60 million Btu/hr and until very recently it had been assumed that a simple combustion device burning at this rate would have substantial physical dimensions. For example, many engineers adopt the rough rule that the output from a combustion chamber will not usually exceed 50,000 Btu/hr/cu ft. On this basis an appropriate combustion chamber, to give an output of 60 million Btu/hr, would have a volume of 1000 cu ft, or, say, it would be 10 ft^3 neglecting wall thickness.

It is with this background of information that it is appropriate to consider the development in Great Britain of an inert gas generator based on an aircraft gas turbine engine.

British "Jet Engine" Inert Gas Generator

Within the last decade D. J. Rasbash, of the Joint Fire Research Organization in Great Britain, has recognized the potentialities of a massive inert gas generator in fighting fires in certain classes of buildings. Faced with the problem of achieving combustion at a high rate per unit volume he turned to the only device then existing which came near to meeting his requirements, viz. the aircraft gas turbine.

The output of a gas turbine is not immediately suitable for use as an extinguishing agent, mainly because its temperature is excessive and to a lesser extent because it has a substantial oxygen content. The National Gas Turbine Establishment looked into these problems. Oxygen content was reduced by the use of an after-burner and cooling was achieved by direct injection and vapourization of water. In the prototype model delivered to the Fire Research Station the composition of the output gas (by volume), at a delivery rate of 45, 000 cfm, was oxygen 7 per cent, nitrogen 46 per cent, CO_2 3 per cent and water vapour 44 per cent.

Extinguishment tests with the apparatus have proven quite successful (7, 8, 9) and appear to confirm the concepts given earlier in this report under the headings "Permissible Oxygen Content of Inert Gas" and "Required Rate of Generation."

In general the equipment will not suppress smouldering and it is intended that firemen should perform this function some time subsequent to the elimination of flaming combustion. The generator is quite versatile and the composition of the gas can be adjusted to make it translucent, a necessary requirement if firemen are to operate in the atmosphere.

Canadian Conditions

Alternatives to conventional fire-fighting techniques are as necessary in Canada as in most other parts of the world, but it is not automatic that the British gas turbine inert gas generator would prove as valuable a tool in Canada as it is likely to do in the U. K. So far as the U. K. is concerned it is not considered essential that the "jet engine" generator should suppress smouldering as it is thought that this activity can be left to firemen at a later stage of the proceedings.

With Canadian constructions, however, one of the most important features of fire fighting is the suppression of fire in the concealed spaces which are to be found in almost all buildings, whether old or new. While this feature makes the massive use of inert gas even more desirable than in the U. K. it also suggests that the oxygen content of the gas should be sufficiently low as to be capable of suppressing smouldering. The oxygen content in the output of the British device, which can be reduced to 7 per cent after the injection of water and 12 per cent before, would seem to be borderline and lower values are desirable.

N. R. C. Development

Achieving a high rate of combustion in a small volume is now considered (11) to be largely a physical rather than a chemical problem and conventional combustion chambers are generally far larger than the limit set by physical considerations. Orders of magnitude are involved and it should not be necessary to resort to gas turbines to achieve, in a conveniently sized chamber, combustion at the rates discussed earlier in this report. In fact it should be possible to design a combustion chamber operating at substantially atmospheric pressure having an output comparable to that of an aircraft gas turbine and a volume of a similar order.

At about the time that the National Research Council was considering this problem, it came to light that such a combustion chamber, was, in fact, being developed by a U.S. company (Black, Sivalls and Bryson of Oklahoma City), and a complete assembly was purchased. At the time, development of a very high output model had not been completed and the model purchased had an output of 6.5 million Btu/hr. If a machine with an output of 40,000 cfm of inert gas is arbitrarily described as "a full-scale inert gas generator," a generator based on a 6.5 million Btu/hr would constitute a one-tenth scale machine.

This choice of scale has proven to be very appropriate for two reasons. Firstly the device was sufficiently small to facilitate experimental development of the water injection techniques. Secondly this scale of inert gas generator needs to be developed in its own right, for application in the fighting of fires in the holds of ships and in inaccessible attic spaces in small buildings. The burner fuel is gaseous propane supplied at a pressure of about 9 psi and at a rate corresponding to a little less than 1 gal/min in liquid phase. Combustion air is supplied at a rate of approximately 1000 cfm, at a pressure not exceeding 20 in. of water, by a 550 volt, 3 phase, 10 hp motor. The output temperature is said to be in the region of 3000°F.

To create a chamber into which water could be injected, stainless steel cylinders of various diameters were attached to the 9-in. diameter burner outlet. Unstable combustion resulted although conditions improved as the diameter of the chamber was increased. It was thought undesirable, from considerations of size, to use a diameter larger than 2 ft and with this diameter of cylinder, other approaches to the problem were investigated. A twofold solution was arrived at. In the burner proper, a flame stabilizer baffle was installed in the region where the fuel and the combustion air first begin to mix, and in the water injection chamber a horizontal vane was installed as illustrated in Figure 1 to cut down the component of rotational velocity in the gas flows in that region.

Water injection was first attempted axially, with hydraulic atomizing nozzles, but proved unsuccessful. Heat transfer to the nozzles was too great and steam instead of water issued from the nozzles. Circumferential injection, however, as illustrated in Figure 1 gave rise to no problems.

A decision as to the diameter of the final outlet duct was then required and 12 in. was considered appropriate. A velocity of about 90 ft/sec could then be expected giving a velocity head of about 1 in. of water. It would certainly not be feasible to attempt delivery through a duct of less than half this diameter for this would give more than four times the velocity and hence a velocity head of some 16 in. of water. The rated delivery pressure of the combustion blower is only 20 in. of water and only a portion of this is available to overcome back pressure due to flow restrictions.

Transition and outlet pieces were installed as illustrated in Figure 1 and once again unstable combustion occurred. It was thought that this resulted from a resonance mechanism in which the plug of gases in the outlet constituted the oscillating mass and the gases in the main chamber gave rise to the forces. A simple calculation gave the resonant frequency as about 50 c/s and while this seemed higher than the frequencies that were apparent there was some agreement as to order.

Acoustic damping was introduced in the form of two stainless steel wool baffles located as illustrated in Figure 1. In order to prevent serious damage to the stainless steel wool over-injection of water was called for and was achieved by the inclusion of three hoses as illustrated in Figure 1. Over-injection had the additional merit of giving even smoother combustion and the noise level from the machine was reduced to little more than the noise from the 10 hp combustion air blower.

With the arrangement as specified both the oxygen and combustion gas contents of the output gases were well under 1 per cent. Thermocouples attached to the wall of the outlet piece and placed in the (wet) gas stream registered a temperature of 75°C.

The theoretical compositions of the input and output of the generator are evaluated in Appendix C but have not yet been accurately investigated experimentally, excepting as mentioned in the previous paragraph. Noting the levels in the propane tank, before and after running, suggests that the scale of input and output is rather greater than that given in Appendix C. The very high water injection requirement also supports this view. The spray nozzles, supplied at a pressure of 120 psi, are providing 12 gal/min and the three $\frac{1}{2}$-in. nozzles, at a pressure of 50 psi, are providing 5 gal/min. Water run off from the equipment is 2 gal/min. This constitutes a thermal loss but is of no real significance.

Figure 2 illustrates the machine in operation.

Further Work

At the time of writing, an experimental investigation of the performance of the machine in extinguishing fires was under way.

It is likely that the generator at its present size will constitute a useful tool for fighting fires in ships' holds and in small inaccessible areas in buildings, such as the attic space. It is therefore desirable that an easily transportable machine should be developed from the N.R.C. experimental generator.

For wider application a larger scale of machine should be developed, in the first instance one with an output of 40,000 cfm, i.e. comparable with the British gas turbine machine. An even higher output model is desirable and some consideration should be given to its development.

The transportation of propane involves pressure vessels and the use of a liquid fuel such as kerosene would be more convenient. Some thought should be given to the possibility of producing a combustion chamber of reasonable dimensions which would accept such a fuel. Doubtless, such a device would be larger than one that burns gaseous fuel and the question is - how much larger it would be. It is conceivable that by the use of high pressure atomizing nozzles a substantial increase in size could be avoided.

Acknowledgements

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TABLE I

OXYGEN CONCENTRATIONS (PREDICTED)

vt/V	Oxygen Concentration: M = 0 (Inert gas) (%)	Oxygen Concentration: M = 5% (Gas with 5% O_2) (%)
0	20	20
1	7.4	10.5
2	2.7	7.0
3	1.0	5.7
4	0.4	5.3
∞	0	5

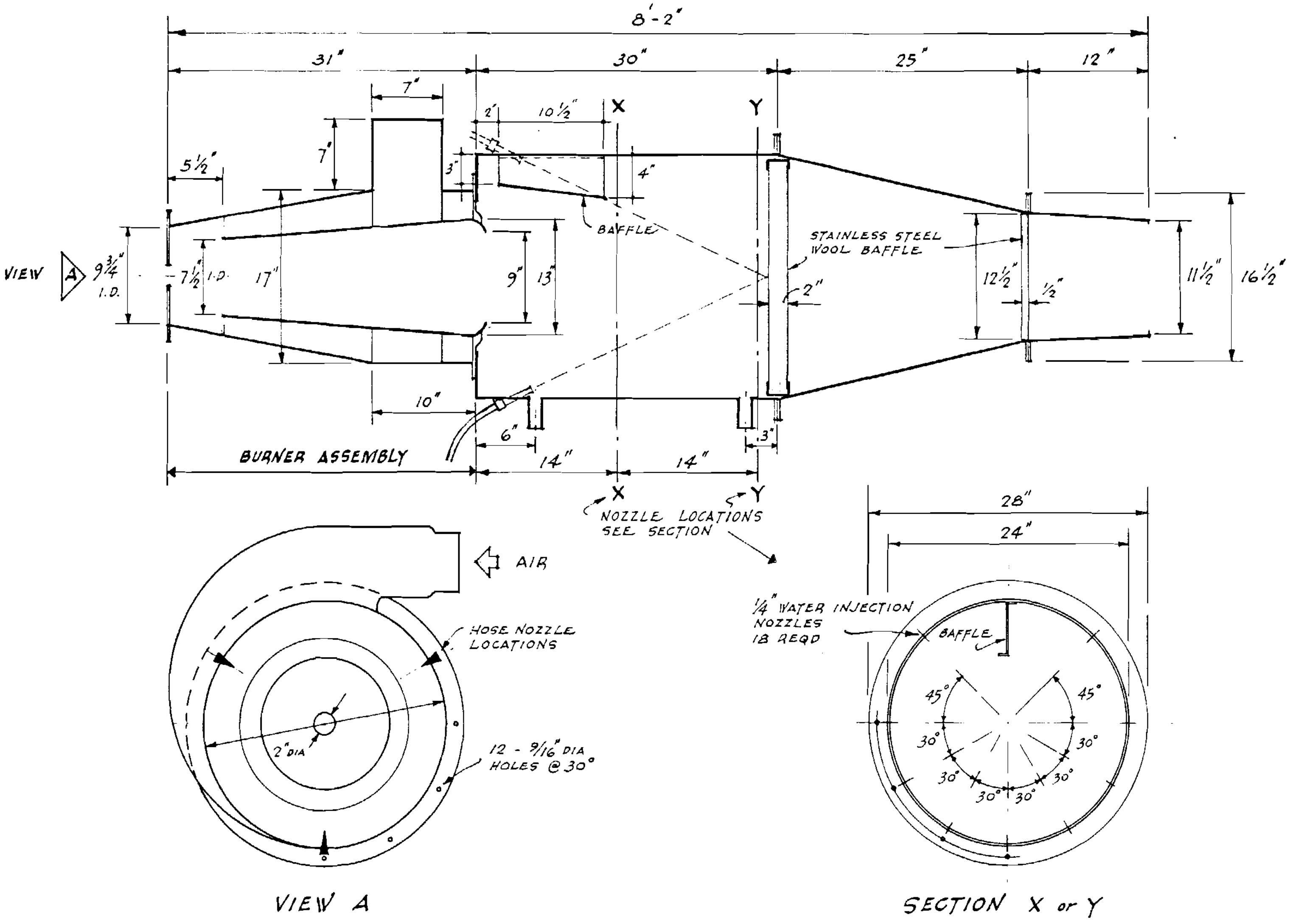

FIGURE 1 WATER INJECTION UNIT, INERT GAS GENERATOR

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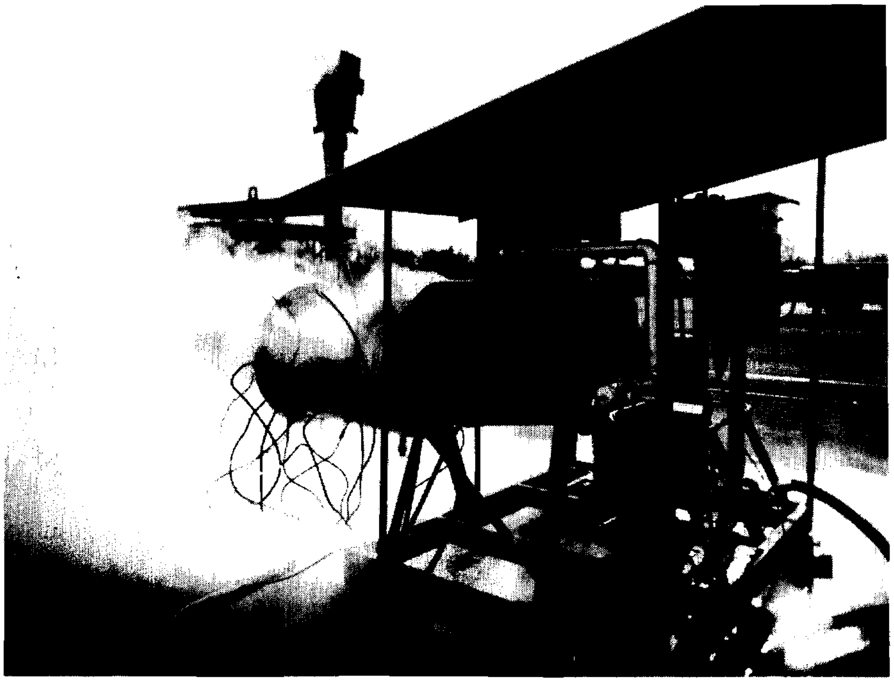

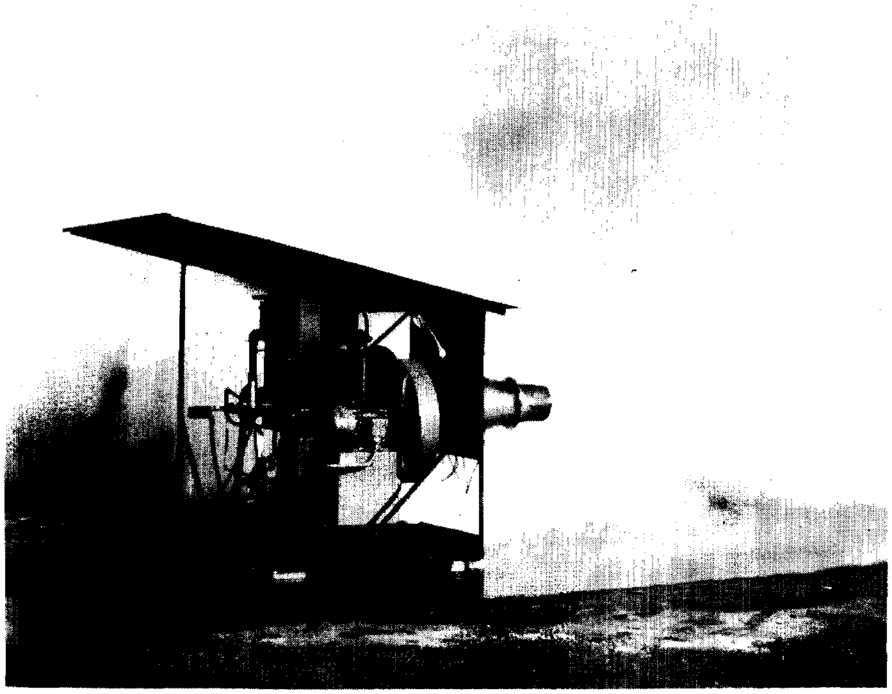

Figure 2 N.R.C. Generator

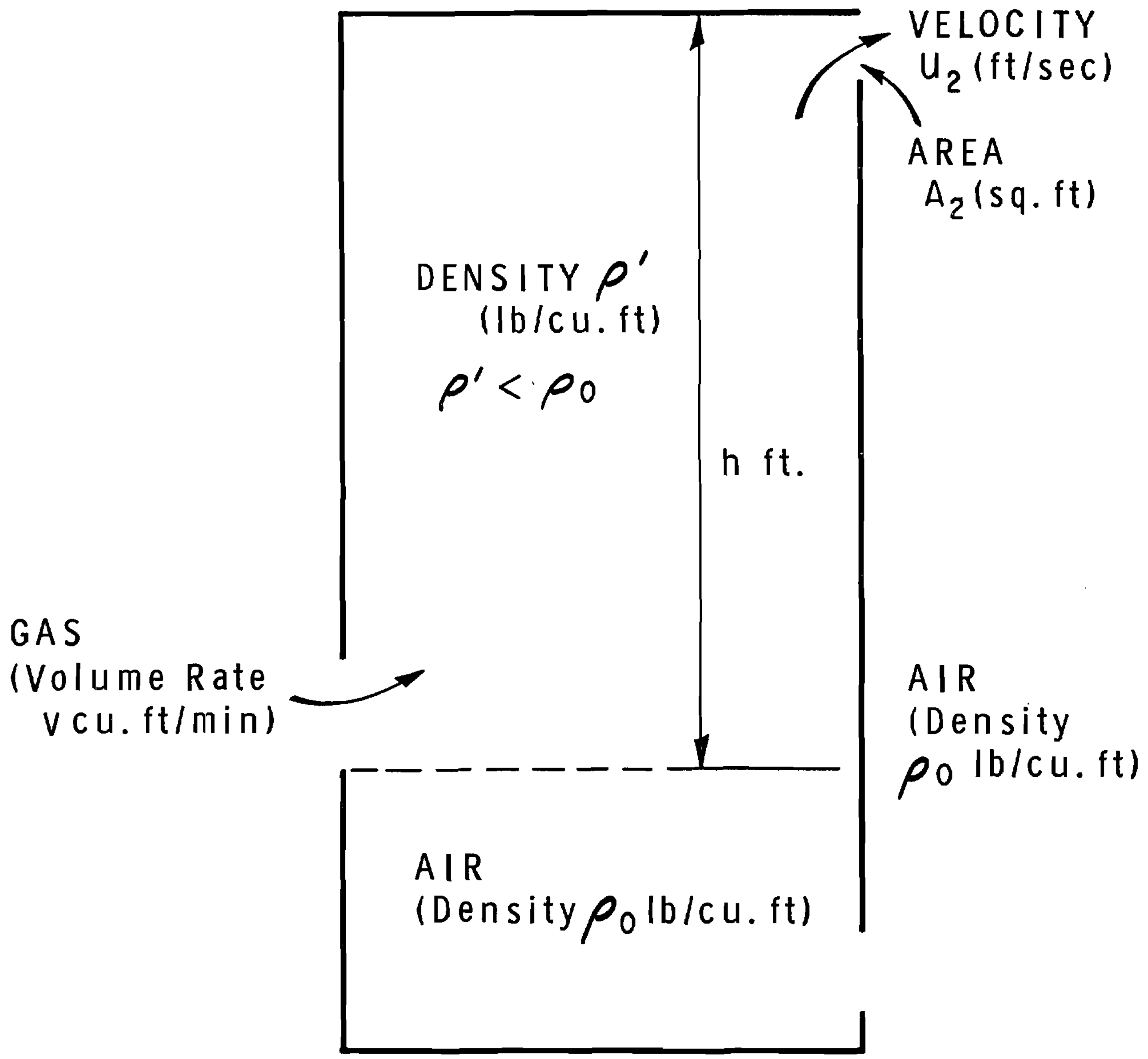

FIGURE 3 GASEOUS LOSSES

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Appendix A

Dilution of Atmospheric Oxygen

Suppose a gas G be injected at a volume rate v into a volume V which originally contained air.

Suppose further that mixing is perfect and that no appreciable pressure differences are involved.

Let the fractional concentration of the gas G at any time t be g $(0 < g < 1)$.

In a time δt the gain of gas G will be $v.\,\delta t$.

The loss of gas G, by the efflux of displaced gases will be $gv.\,\delta t$ so that the net gain of gas G will be $(1 - g)\ v.\,\delta t$.

The change in concentration δg of the gas G will be $(1 - g)$ $v.\,\delta t/V$ so that

$$dg/dt = (1 - g)\ v/V$$

Integrating this equation and invoking the boundary conditions $g = 0$ at $t = 0$ and $g \rightarrow 1$ at $t \rightarrow \infty$

$$g = 1 - e^{-vt/V} \tag{1}$$

If the gas G is taken to have an oxygen concentration m and air to have an oxygen concentration of 0.2 (i.e. 20 per cent), the oxygen concentration n of the mixture will be

$$\begin{aligned} n &= m.\,g + 0.2(1 - g) \\ &= m(1 - e^{-vt/V}) + 0.2.\,e^{-vt/V} \\ &= m + e^{-vt/V}(0.2 - m) \end{aligned} \tag{2}$$

If n and m are expressed as percentages M and N Equation (2) becomes

$$N = M + e^{-vt/V}(20 - M) \tag{3}$$

Table I relates N and vt/V for values of M of zero and 5 per cent.

Appendix B

Gaseous Losses

Part 1 - General

Consider a gas, less dense than air, injected at a rate v cu ft/min into an enclosure at the top of which there is an opening of area A_2 (Figure 3). The equilibrium condition which will be established will be such that the pressure difference either side of the outlet gives rise to a flow equal to the inlet flow. Assuming the gases within the enclosure to be effectively stagnant and stratified, and the flow coefficient at the outlet to approximate to 0.6 (5), the expression governing the flow will be

$$h\ (\rho_o - \rho^1)\ g = 1.39\ \rho^1\ u_2^{\ 2} \tag{4}$$

where

g is acceleration due to gravity and the remaining symbols are defined in Figure 1.

Mass flow continuity considerations give

$$A_2 u_2 = v/60$$

where v is the injection rate in cu ft/min and the factor 60 is necessary owing to inconsistency of units.

$$\text{Hence } A_2 - 3.47.10^{-3}\ (v/h^{\frac{1}{2}})\ [\rho^1/(\rho_o - \rho^1)]^{\frac{1}{2}} \tag{5}$$

Part 2 - N.R.C. Generator

The density ratio for the output of the NRC experimental generator is most easily evaluated by taking density as proportional to mean molecular weight/absolute temperature.

The composition of the gas is $3CO_2 + 20N_2 + 48H_2O$ so that its mean molecular weight is 21.9. The mean molecular weight of air is about 29.

Taking the temperature of the injected gas as 100°C and ambient temperature as 0°C, the density ratio in Equation 5 becomes

$$[\rho^1/(\rho_o - \rho^1)]^{\frac{1}{2}} = [(21.9/373)/(29/273 - 21.9/373)]^{\frac{1}{2}}$$

$$= 1.11$$

Hence

$$A_2 = 3.86.10^{-3} \, v/h^{\frac{1}{2}}$$

where

the units of A are sq ft

those of v are cu ft/min

and those of h are ft.

Appendix C

Combustion and Vapourization Processes

If a stoichiometric mixture of air and propane is burned, the heat output of 1 gm mole of propane will be 488.5K cal (10). This figure applies to the conditions giving generated water in the vapour phase. If the gases are assumed to be at 100°C a further correction (approx. 11K cal) is associated with the heating of the inert gases in the combustion air.

The heat available to vapourize water will therefore be 477K cal/gm mole of propane. If it is assumed that the heat required to raise the temperature of water from an arbitrary ambient temperature to 100°C and to vapourize it is 600 cal/gm then the quantity of water which could be vapourized is $477,000/600 = 795$ gm $\doteq$ 44 gm mole.

The expression for the complete combustion and vapourization process, assuming air to be composed only of O_2 and N_2 is therefore:

$$C_3H_8 + 5O_2 + 20N_2 + 44H_2O\,(\text{liquid}) = 3CO_2 + 4H_2O(\text{vapour}) + 20N_2 + 44H_2O(\text{vapour})$$

$$= 3CO_2 + 20N_2 + 48H_2O(\text{vapour})$$

Thus for every molecule of propane which is burned the output will contain 71 molecules.

The rated heat output of the burner acquired by NRC is 6.5×10^6 Btu/hr and adopting the higher value of the heat of combustion of propane (21,646 Btu/lb) (10) the input and output of the generator will be constituted as follows:

5.0 lb/min of propane (0.86 Imp gal/min) + 89 lb/min of air (1085 cu ft/min at 0°C) + 90 lb/min of water (9 Imp gal/min)

= 15 lb/min of CO_2 (155 cu ft/min at 75°C) + 64 lb/min of nitrogen (1040 cu ft/min at 75°C) + 98 lb/min of water vapour (2600 cu ft/min at 100°C)

= 1195 cu ft/min of "natural gases" (at 75°C) + approx. 2600 cu ft/min of water vapour

$\doteq$ 3800 cu ft/min total.