

FIRE SUPPRESSION USING SOLID PROPELLANT GAS GENERATOR TECHNOLOGY

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Primex Aerospace has demonstrated the use of solid propellant gas generator (SPGG) technology as an effective, environmentally benign alternative to Halon **1301** in fire suppression applications. In this approach, an intimately **mixed** fuel/oxidizer solid propellant blend is combusted in a pressurized gas generator (GG); the combustion gases (a mixture of CO₂, N₂ and H₂O) **are** then vented from the GG into the fire zone. This mixture of inert gases rapidly suppresses various fire scenarios.

SPGG fire suppression technology has been found to be effective in aircraft engine nacelles drybays and ground vehicle engine compartments. A combination of live fire testing and agent concentration distribution studies has indicated that PAC's FS-0140 suppression systems **are** weight- and volume-competitive with comparable Halon-1301 suppression systems.

The SPGG technologies described above can be competitive with Halon suppression systems, particularly if their distribution in the volume-of-choice is well understood. To this end, we have obtained temporally- and spatially- resolved analyses of CO, and O₂ concentration levels over the course of the fire suppression test event. Measurements in highly turbulent conditions indicate that both dilution/inertion and flame strain effects contribute to the fire suppression mechanism.

Introduction

The majority of ~~fire~~ extinguishing systems used today, in applications such as commercial and military aircraft, ground vehicles (autos, trucks, buses) and surface ships rely on the chemical agent Halon 1301, with chemical formula CF_3Br . This substance belongs to a large class of materials known as Halons; these materials are generally composed of brominated or chlorinated fluorocarbon compounds, with typical formulas CF_3Br (Halon-1301) and CF_2ClBr (Halon-1211). Recently, international cooperation has resulted in an agreement (the "Montreal Protocol", 1987) to discontinue both production and use of all Halons because of evidence that Halons contribute to the depletion of stratospheric ozone. This has led to a search for alternative, environmentally friendly agents that act in a similar manner to Halons for the suppression and extinction of fire.

The search for alternatives to Halon-1301 has focused in large part on agents that closely mimic the chemical and fluid mechanical properties of CF_3Br , such as other halocarbon systems. Concerns about the effects of bromine on ozone depletion potential (ODP) narrowed this search to fluorocarbons or hydrogenated fluorocarbons, e.g. HFC-227ea and HFC-125, but these are much less effective per unit mass or volume with respect to Halon 1301. There has been some recent attention directed towards the use of CF_3I as an alternative agent(1); its efficacy is hampered by concerns regarding high altitude emissions. Comparison of bottled inert gas, e.g. nitrogen or carbon dioxide, are also quite unfavorable with respect to Halon-1301, due in particular to the large volumes required for agent storage of these compressed gases.

A new approach to fire suppression is based upon technology similar to that used in automobile airbag inflators. In this approach the fire suppression agent is a mixture of inert gases which are stored not in pressure bottles but in the form of solid propellants, which on combustion in a solid propellant gas generator (SPGG), produce large quantities of nitrogen, carbon dioxide and water vapor. The compact nature of the SPGG device makes it a remarkably efficient means for chemically storing gaseous agents in a solid form. Early developments of this approach were outlined in 1986(2) with further refinements coming later(3).

Table 1 presents an analysis of various fire suppression agents based on cup-burner concentrations(4). A comparison of extinction concentrations and typical storage conditions indicates that the best candidates from among known FC's and HFC's require 2-3 times the volume and 2-2.5 times the weight of Halon-1301 for equivalent effectiveness. Nitrogen as a fire suppression agent is weight-competitive with Halon-1301 but suffers because of the large column associated with its storage. Carbon dioxide also appears competitive, but this overlooks the complexities associated with gas blowdown from a CO₂ bottle. However, when taking into

consideration agent density under storage conditions, as well as the added volume required for a pressurant gas, it is clear that even for a solid propellant formulation which yields 50% gas, volumes required for agent storage approach that of Halon-1301; high-efficiency propellant formulations meet both mass and volume envelopes of Halon systems.

In a SPGG, the fire suppression agent is stored at atmospheric pressure in hermetically sealed units, both contributing to long service lifetimes. These gases can be produced in timeframes ranging from -50 ms to several seconds, and the devices are operable over a wide range of temperatures. The gaseous agents created when functioning a SPGG - N₂, CO₂, H₂O - are chemically benign and pose no threat to atmospheric ozone. The use of SPGG's for fire suppression was the subject of a recent workshop(5).

Functioning of a SPGG fire suppression device is quite similar to that of more conventional bottle blowdown systems in that both begin with electric squib initiation . In the case of SPGG's, the squib initiates the combustion of the solid propellant grain or grains, which may be present in the form of pills similar in size to aspirin tablets, or larger in size like a salami. The propellant formulation, containing an intimate mixture of fuel and oxidizer plus additives, rapidly combusts to generate large amounts of gas. The inert gas blend is then exhausted into the fire zone to effect suppression.

Testing

Fire suppression efforts at PAC have emphasized the use of SPGG technology in drybay and engine bay applications of military aircraft(6) as well as in engine compartments of military land vehicles; these areas are unoccupied and are not subject to rigid restrictions in terms of gas composition and output temperature, so long as the agent is delivered quickly. Drybays are not relevant in commercial aircraft, but commercial vehicles do have need for environmentally friendly fire suppression systems in engine compartments, cargo holds and occupied spaces.

PAC initiated research and development efforts to apply airbag technology to fire suppression units in 1992. This effort resulted in a new gas generator propellant ideally suited for fire suppression applications. This propellant (FS-0140) has been tested both by itself as an all-solid system and also as a solid/liquid hybrid system here alternative Halon substitutes are used with FS-0140. PAC has conducted extensive testing to develop several fire suppression concepts and recent testing has demonstrated that both the all-solid and the hybrid systems are effective in suppressing fires using systems comparable in volume to a Halon 1301 system.

Live fire testing in a simulated U.S. Navy aircraft drybay took place at the Naval Air Weapons Center (NAWC), Weapons Vulnerability Division, China Lake, CA. There, testing using small and medium caliber High Explosive Incendiary (HEI) ammunition indicated that

PAC's solid system was the most effective unit available when compared to Halon-alternative fluorocarbons. This testing included pressurized hydraulic lines and an airflow equivalent to an aircraft traveling at 400 knots. Propellant loads were deduced from the analytically-derived development design based on their demonstrated fire suppression capability.

As part of this test effort, PAC developed an agent concentration analyzer (Figure 1) for correlation of fire suppression effectiveness and spatial and temporal distribution of agent. Agent, measured as [CO₂], and air displacement, measured as [O₂], are measured independently. CO₂ concentrations are measured using IR absorption with a chopped 10Hz IR beam. O₂ analyses are measured using an electrochemical technique sensitive to the difference in oxygen concentrations measured relative to air.

The results at both NAWC and WPAFB verified that the quantity of agent required for a production design fire suppression system amounts to a 10–15% weight increase over a comparable Halon 1301 system, at similar system volume.

Hybrid SPGG Systems

By their very nature, the gases output from a SPGG are very hot. Conditions in the combustion chamber typically call for temperatures in excess of 1500 °K and pressures of at least 1000 psi. Certain applications require significantly lower gas temperatures. These cooler temperatures can be readily achieved through the use of hybrid cooling technologies.

PAC has developed a variety of hybrid gas generators that utilize a solid propellant gas generator to heat and expel a liquefied fluid or refrigerant for other inflation applications. These systems typically use a low vapor pressure fluid such as water, CO₂, or fluorocarbons that are rapidly vaporized and are expelled by a solid propellant gas generator exhaust, e.g, Table 2. PAC-developed hybrid systems are currently being produced for helicopter float inflation, torpedo recovery float inflation and are seriously being considered as a new means for inflating automobile air bags.

PRIMEX has extended SPGG-hybrid technology to fire suppression applications. One particularly attractive goal of this effort is the development of a water-based hybrid system and delivery of fine water mists to the fire zone. This goal contains several great challenges, both in terms of the necessary temperature extremes in possible use, and also in the reproducible delivery of fine water mists. Preliminary tests indicate that the heat generated by solid propellants under combustion conditions may be sufficient to heat and expel even frozen water beds.

Mechanism of Suppression

One of the most general descriptions of the mechanism of **fire** suppression evokes the Damkohler number, D (7). This number is defined as

$$D = \tau_{\text{flow}}/\tau_{\text{chem}},$$

where τ_{chem} is the characteristic **flow** time of the combustion process, and τ_{chem} is the characteristic chemical reaction time of the combustion process. Fires **are** extinguished when the ratio D is below some critical ration D_{crit} . Minimization of D can occur at short flow times τ_{flow} , or long chemical reaction times τ_{chem} . Factors contributing to long chemical reaction times are cooler temperatures and less efficient combustion reactions via, e.g., dilution effects or radical trapping processes. Factors contributing to short flow times **are** high airflow and/or high agent discharge rates.

An important mechanistic feature in solid propellant gas generator fire suppression systems is the high concentration of inert **gas** generated during the combustion process. Typically, an intimate propellant mixture of solid fuel and oxidizer is ignited at high pressure in a gas generator. Combustion yields large amounts of a mixture of inert gases (CO_2 , N_2 , H_2O). Since these gases are a result of a combustion process, they are typically hot ($1000 - 1500^\circ\text{C}$ or $1800 - 2700^\circ\text{F}$ @ 1000 psi). The products of this combustion are then exhausted from the gas generator and directed into the fire zone.

The effectiveness of this inert gas is enhanced by the high specific volume of the hot gases resulting from the combustion process. On entry into an open fire zone, the hot gases displace air, and consequently drop the oxygen concentration quickly. Hydrocarbon combustion is largely quenched when oxygen levels fall below 15%(8), so total inert gas concentrations of 28% are expected to be sufficient for flame extinction. This concentration is close to levels expected for CO_2 , N_2 , and H_2O based upon cup burner testing.

PRIMEX designed and constructed an agent concentration analyzer (described above, Figure 1) used on full scale fire suppression testing of SPGG technology on military aircraft engine bay and drybay platforms. This testing has demonstrated that fires **are** consistently extinguished under conditions where oxygen levels may be as low as 12%. However, suppression has also been observed in conditions where oxygen concentrations, e.g., Figure 2, were higher than 15%. This suggests that factors other than oxygen starvation or cooling are contributing to flame suppression by SPGG technology.

In order to probe the effects of flame strain on the suppression event, a turbulent spray burner TSB fixture has been constructed at PRIMEX and modeled after the design of NIST(9).

This device mimics many critical features of an idealized engine bay fire. A **small** gas generator was constructed, allowing evaluation of 1-gram quantities of propellant under conditions of a baffle **stabilized** spray flame. **This** device is instrumented to provide collection and analysis of important information such as temperature, pressure and oxygen concentration. Testing using the TSB unit provides a means for both assessing relative effectiveness of various solid propellant compositions as well as the mechanism of action of the SPGG devices. In this way, mechanistic information can be fed back to develop and refine solid propellant formulations and gas generator design to yield an optimized **SPGG** fire suppression system.

Typical operating conditions for PAC's spray burner were airflow of 22 g/s, fuel flow of 0.28 g/s JP-8 through a 45" cone-spray furnace nozzle, all in a 50 mm dia tube; a 250 msec discharge was taken for baseline purposes. **This** represents an equivalence ratio of 0.18 for a 13 kilowatt flame, with lower airflow rates and a more fuel-lean condition than the NIST baseline. Laboratory testing of **this** TSB, Figure 3, closely mirror baseline data published by NIST for nitrogen pressure bottle discharge, after correcting for the lower airflows, different air-fuel stoichiometry and discharge times. Measurements for carbon dioxide indicate that the mass fraction of CO₂ is slightly greater than that of N₂; this is in accord with NIST's correlation of mass efficiency and heat capacity (per unit mass)(7). Mixtures of N₂/CO₂ show behavior between that of the two end members.

Future State of SPGG Fire Suppression

The technology of solid propellant gas generator fire suppression systems is relatively young and has several areas ripe for technical improvement. Cooler exhaust temperatures may be important where agent distribution lines are constructed of lower temperature materials, e.g. aluminum. PAC has developed both cooler propellant formulations and gas cooling concepts, e.g. hybrid technologies, to meet these needs.

Additives which augment the "physical" (dilution, heat capacity) effects of inert gases with "chemical" effects, e.g. radical traps, have been shown to significantly enhance the effectiveness of SPGG's. Early testing indicate that efficiency enhancements of 30-50% are possible through suitable choice of additive.

Some applications, such as inerting fuel storage areas or occupied spaces require extended suppression times. The most efficient means to accomplish this is through the use of large grains of propellants housed in a single unit of gas generator hardware. However, large grains present a special developmental challenge.

Summary

The technology of solid propellant gas generator fire suppression systems is relatively young, yet has already achieved several notable successes in fire protection of **military** aircraft engine bay and drybay areas. SPGG's available today offer solutions which **are** weight and volume competitive with Halon-1301. **Gas** generator technology is flexible and can be designed to meet a range of application-specific requirements, such **as** fast or slow response times. SPGG hybrid systems provide a means controlling agent discharge over a range of times and temperatures. Mechanistic studies have shown that SPGG's function through a combination of dilution and flame strain effects.

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Table 1

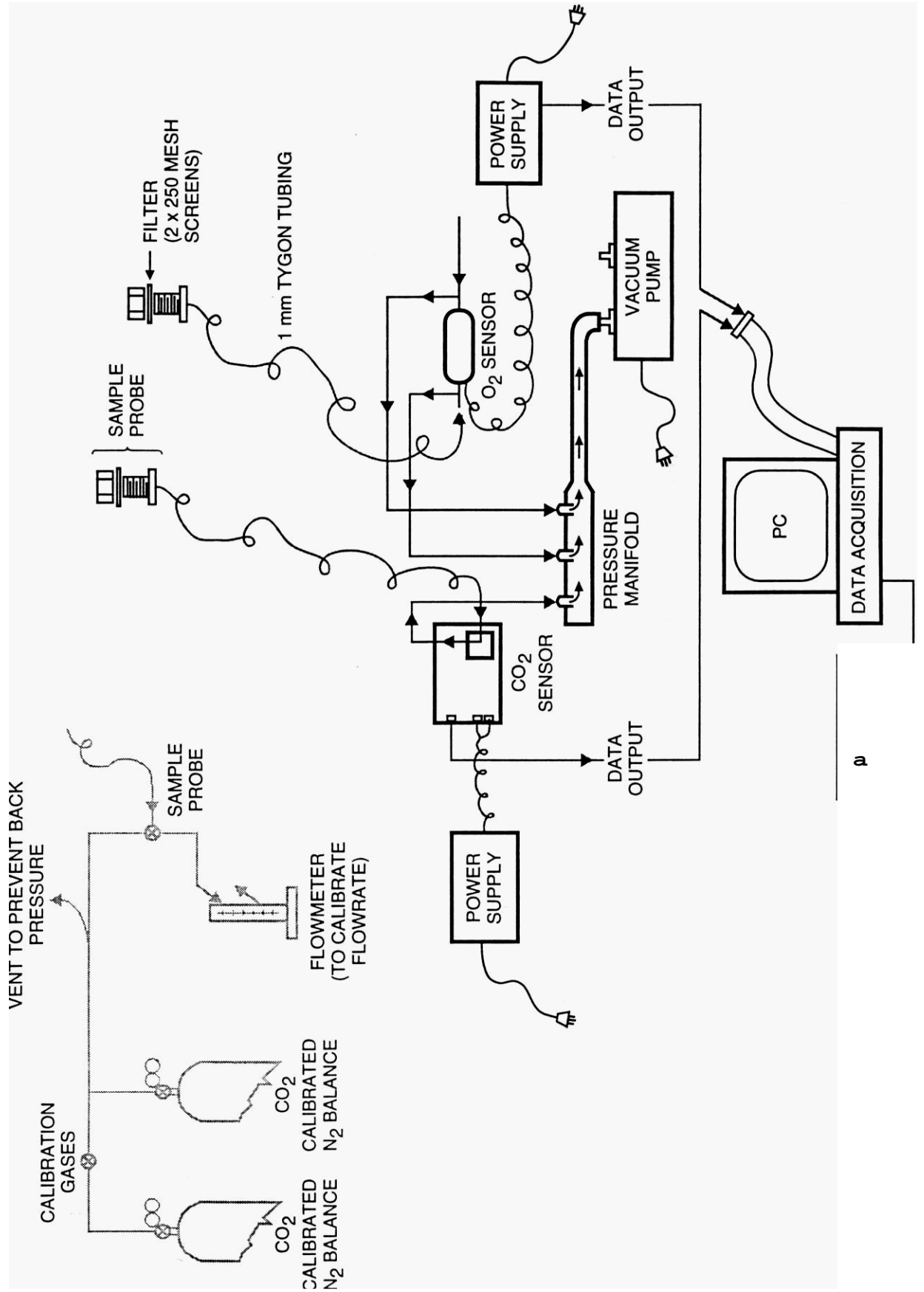
HALON + ALTERNATIVES

	Extinction Concentration, %	Storage Density g/cc	Agent Extinction Mass, g/L	Agent Extinction Volume, cc/L	Agent Storage Volumes, * cc/L
Halon	3.5	1.55	0.21	0.14	0.28
HFC-227ea	5.9	1.40	0.41	0.29	0.58
HFC-125	9.4	1.19	0.49	0.41	0.82
N ₂	30	0.16	0.34	2.1	2.1
CO ₂	20	0.61	0.36	0.59	0.59
SP @ 50% GBS	25	2.5	0.31 (0.62 g Prop)	0.25	0.25
SP @ 90% Gas	25	2.5	0.31 (0.34 g Prop)	0.14	0.14

* NOT: need 2x V_{crit} to accommodate H₂ pressure

CONCLUDE: Solid propellants provide agent storage volumes at least as low as Halon-1301 systems and 2-5 less than current HFC systems.

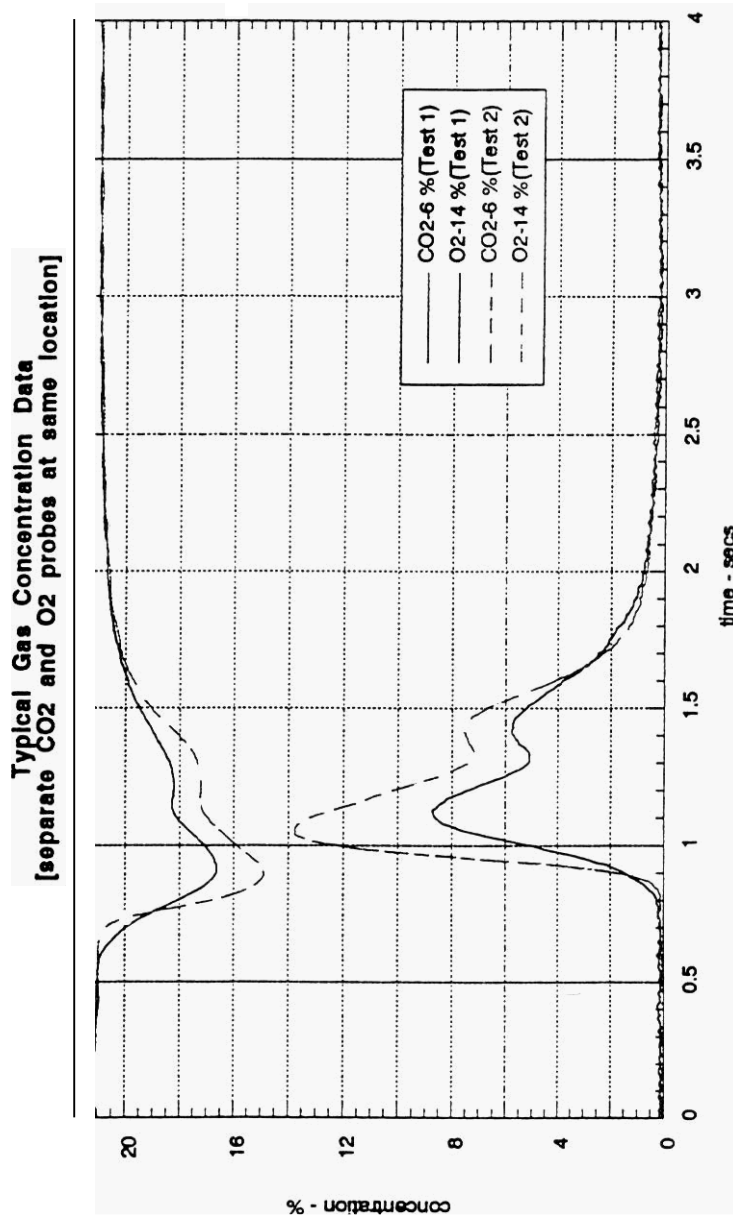
Figure 1
Gas Concentration Measurement System



C11259-51-A

Figure 2
AGENT CONCENTRATION ANALYSIS

- CO₂
- O₂
- Spatial and temporal distribution



PRIMA FIRE SUPPRESSION FLUOROCARBON AGENTS

Table 2

Liquid Coolants, Low Vapor Pressure				
Agent	Chemical Formula	Supplier	bp, °C	bp, °F
HFC-227 ea	C ₃ H ₇ F ₇	GLC FM-200	-15	5
HFC-236 fa	C ₃ H ₂ F ₆	DuPont FE-36	-1	30.2
PFU-614	C ₆ F ₁₄	3M CEA-614	56	132.8
PFU-410	C ₄ F ₁₀	3M CEA-410	-2	28.4
FIC-1311	CF ₃ I	Pacific Scientific "Triodide"	-22	-7.6
water	H ₂ O		100	212

Figure 3
Beta vs. flow rate

