Naval Research Laboratory

Washington, DC 20375-5000

AD-A207 346

Tests of Halon 1301 Test Gas Simulants

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February 28, 1989

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REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6424	5 MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory	6b OFFICE SYMBOL (If applicable) Code 6180	7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION Naval Sea Systems Command	8b. OFFICE SYMBOL (If applicable) SEA 05R23	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20362	10 SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO 63514N	PROJECT NO S1565-SL	TASK NO DC01FFS-03	WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)

Tests of Halon 1301 Test Gas Simulants

12. PERSONAL AUTHOR(S)

(See page ii)

13a. TYPE OF REPORT Interim	13b. TIME COVERED FROM 1/87 TO 5/88	14. DATE OF REPORT (Year, Month, Day) 1989 February 28	15 PAGE COUNT 81

16. SUPPLEMENTARY NOTATION

*Hughes Associates, Inc., Wheaton, MD 20902

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Halon 1301
			Halon 1301 simulants

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

All new and retrofit installations of Halon 1301 total flooding fire protection systems in shipboard machinery spaces require full acceptance discharge test. It is desirable to use a suitable simulant test gas in these tests in view of current and future regulation of Halon 1301.

Sulfur hexafluoride, SF_6, and chlorodifluromethane R-22, were identified as candidate simulants on the basis of their similarity in physical properties to Halon 1301. These two candidate were then evaluated on the basis of leakage from an enclosure.

SF_6 was determined to be an excellent simulant for Halon 1301 when considering leakage from an enclosure. Further testing of SF_6 and R-22 is planned for other important aspects of Halon 1301 systems, i.e., flow hydraulics, initial mixing. Fluoride Sulfur Compound, chlorine compounds. (Mytra)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL H.W. Carhart	22b. TELEPHONE (Include Area Code) (202) 767-2262 — 22c OFFICE SYMBOL Code 6180

DD Form 1473, JUN 86 — Previous editions are obsolete.

S/N 0102-LF-014-6603

12. PERSONNEL AUTHORS

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Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	

By
Distribution/
Availability Codes

Dist	Avail and/or Special
A-1	

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TESTS OF HALON 1301 TEST GAS SIMULANTS

1.0 INTRODUCTION

All new and retrofit installations of total flooding Halon 1301 (Bromotrifluoromethone) systems in shipboard machinery spaces require a full acceptance discharge test using Halon 1301 or approved simulant test gas. The purpose of this project is to identify a suitable Halon 1301 simulant and demonstrate its validity for use during acceptance discharge testing. Simulant test gas use and development is desirable for the following reasons.

1.1 Ozone Depletion

The primary reason for simulant gas development is the issue of stratospheric ozone depletion. Recently the World Meteorological Organization (WMO), the National Aeronautics and Space Administration (NASA), and other experts of the scientific community have linked the depletion of the stratospheric ozone layer to chlorofluorocarbon and Halon emissions [1,2,3]. Estimates by the National Fire Protection Association (NFPA) and the Environmental Protection Agency (EPA) reveal that most Halon 1301 emissions are due to fire protection system testing [4,5]. In addition, Halon 1301 is

per pound more ozone destructive than many of the
chlorofluorocarbons [3]. Initially NFPA's Committee on
Halogenated Fire Extinguishing Systems proposed for action in
1987 a measure requiring mandatory full discharge testing
using Halon 1301 [6]. However, current technical information
regarding ozone depletion has caused the NFPA to retract this
requirement. Regulatory measures have begun to be taken. An
International protocol was signed in September 1987 that,
upon ratification, would limit production of many
chlorofluorocarbons and Halon 1301 to 1986 production levels
[7]. The protocol would also call for production level cuts
for many chlorofluorocarbons in two stages, in 1993 and 1998,
for a total cut of 50%. Halon 1301 is excused from the
production cuts but its production would be capped at 1986
production levels starting in 1992.

1.2 Current Simulants

The primary Halon 1301 simulant used in the past by the
private sector is dichlorodifluoromethane (R-12) [8]. R-12
has been found not to simu'ate the flow or leakage
characteristics of Halon 1301, and is rarely used today.
Testing of chlorodifluoromethane (R-22) as a possible
discharge gas simulant is underway [9]. Both, as shown in
their chemical names, are chlorofluorocarbons and are,
therefore, potentially subject to future EPA regulations.
However, the relative ozone depletion potential of R-12 and

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R-22 is much less than Halon 1301 [1,3]. The most important
aspect associated with R-12 and R-22 is their questionable
ability to successfully simulate Halon 1301. To date R-12,
R-22, and the test procedure in which they are utilized have
never been physically verified with respect to flow,
discharge, mixing, leakage, stratification, etc. This
argument has been the primary reason supporting the current
Navy position of not allowing the use of Halon 1301 simulants
during acceptance testing.

2.0 TECHNICAL ISSUES

Physical characteristics of shipboard machinery spaces
make them unique with respect to typical total flooding Halon
1301 applications. For example, machinery spaces may contain
large volumes, high vertical distances, potential atmospheric
temperature gradients, and numerous obstructions. Therefore,
several technical issues must be understood regarding the
potential effects on Halon 1301 before an acceptable simulant
gas can be found. The predominant interrelated issues that
must be understood are:

- mixing

- stratification

- leakage

- two phase flow hydraulics

2.1 Mixing

Halon 1301 if properly mixed with air, will not stratify even though Halon 1301 is approximately five times heavier than air. Shipboard machinery spaces represent a large volume, numerous obstructions, potential temperature gradients, and large vertical dimensions. The combined effects of these physical characteristics represent the largest challenge in terms of attaining proper mixing. Many times, nozzles and system piping can not be arranged as designed because of physical obstructions. Piping directional changes as well as changes in nozzle type and placement play important roles in successful Halon 1301 mixing. Therefore, understanding the process of Halon 1301 mixing and the effects of all the potential variables is important.

2.2 Stratification

Halon 1301 stratification may occur for several reasons. Simple buoyancy effects induced by localized temperature gradients and enhanced by high vertical elevations could cause stratification. Many times normal operating temperatures of shipboard machinery spaces can easily exceed 38°C (100°F). This action can be further enhanced by potentially large vertical openings, which in some cases span three decks. As discussed previously, stratification can also result because of poor mixing. When Halon 1301 is not

properly mixed it simply settles to the lower levels of the space, resulting in higher concentrations at the floor and lower or no detectable concentrations at the ceiling. Stratification can also be induced by gas leakage from the space, which is discussed in the next section.

2.3 Leakage

Ideally, to ensure the proper Halon 1301 concentration the space being protected must be entirely air tight. If it is not air tight the Halon 1301 air mixture will leak from the space. Leakage near the floor tends to be particularly bad because the resulting Halon 1301/air mixture is heavier than ambient air. (A 6% by volume Halon 1301 mixture is 31% heavier than air). If a leak is encountered, the Halon 1301/air mixture will exit the space in a similar fashion as water flowing from a leaking pail. During this leaking action fresh air is drawn into the space and accumulates near the ceiling, replacing the lost Halon 1301/air mixture. As a result, diminishing Halon 1301/air mixtures always begin near the space ceiling. Obvious examples of potential shipboard leakage paths are cable, ducting, pipe penetrations, and unsealed doors, etc.

Shipboard machinery spaces also have large unenclosable openings (uptakes) at high levels in the space. With respect to Halon 1301/air mixtures the effects of these openings are largely unknown. Although, if the space possesses low level

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leaks these uptakes would provide an ideal source of replacement fresh air. Conversely, if the space were tight with the exception of the uptakes, very complicated air flows induced by large temperature gradients could occur. Another important aspect is a definable relationship between mixing and leakage. Provided there are no leakage paths poor initial mixing can be overcome by mechanical mixing. For example, ordinary fans placed in the space would recirculate or stir the Halon 1301/air mixture until homogenous.

2.4 Flow Hydraulics

Halon 1301 possesses unique two phase flow characteristics when discharged throughout typical piping networks. In fire protection systems, Halon 1301 is stored in the liquid phase at pressures exceeding 20.8 kg/cm^2 (300 psi). Upon system discharge, liquid Halon 1301 begins to transit the piping network, while experiencing a reduction from the original storage pressure. Liquid flashing starts to occur where the reduced storage pressure begins to equal the vapor pressure of Halon 1301 (approximately 14.0 kg/cm^2 (200 psi)at 21°C (70°F)). During this flashing stage drastic nonlinear changes occur in the pressure and velocity profiles. The nitrogen initially dissolved in the Halon 1301 further complicates the flow. All this causes classical single phase flow equations, such as Chezy and Moody, to become non-applicable [10]. To overcome this complexity

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existing calculation methods rely on correlations developed from empirical data. NFPA 12A presents two representative methods [11]. The first method is based on charts and graphs and is only valid for simple balanced systems. For example, those systems in which all pipe sizes and lengths are equal and all nozzles have the same flow rates. As expected, this method has one obvious drawback in that it is not applicable to unbalanced systems. The second method shown in NFPA 12A uses a two phase flow equation that requires rigorous calculation. Using this equation for relatively simple unbalanced system may require the aid of a computer. Because the current state-of-the-art is forced to rely on complicated flow equations that are sometimes based on questionable empirical data, most U.S. vendors have opted to develop their own proprietary computer calculation programs.

These computer programs are, however, many times subject to listing by U.L. in accordance with standard 1058 [12]. A questionable area of this standard is that it only evaluates the bottom line of any program. That is, it compares the predicted Halon 1301 concentration to the calculated, only under the conditions set forth by the owner. For example, a particular program may only be valid for a certain size system and a 30/70 percent split at any given tee. It can be seen that many areas of uncertainty exist regarding the actual flow physics. The physics experienced by Halon 1301 during transit through any pipe network undoubtedly effects

many important characteristics of the final concentration found in the protected enclosure. Obvious examples, as discussed previously include, flow, discharge, mixing, stratification, etc. Therefore, before an acceptable overall simulant can be developed we must understand and quantify these effects using Halon 1301. At the very least, this highlights the need to locate a simulant that possesses approximately the same physical properties of Halon 1301.

3.0 TEST GAS SIMULANT

In the initial phase of this project the approach involved identifying candidate simulant gases, preferably a suitable non chlorofluorocarbon test gas or gas mixture that would not be subject to future (EPA) regulation. The use of reduced volumetric concentrations was also evaluated. Preliminary alternative approaches which were discontinued included:

- development of simulant chlorofluorocarbon test gas using existing test protocols, i.e. R-12, R-22, similar test agent concentrations,

- use Halon 1301 in reduced scale concentrations, i.e. 1% or 2% instead of actual design concentrations and modified test protocols.

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3.1 Desired Simulant Characteristics

An acceptable simulant must possess several key physical and chemical characteristics. A simulant gas or gas mixture should be non chlorofluorocarbon and possess similar physical properties as Halon 1301. Other important interrelated characteristics that are desired include:

- Environmentally safe

- Clean

- Non-Toxic

- Physically accurate simulation

- Inexpensive

- Easily detectable

3.2 Environmentally Safe/Non-Toxic/Clean

Beyond the issue of stratospheric ozone depletion, the simulant must be non-damaging to other areas of the environment. The simulant is also required to be non-toxic and clean. Because it will be discharged on an active ship, any issues related to toxicity can not be tolerated. For similar reasons, the simulant must also be clean and non-corrosive. Time and manpower concerns mandate that the machinery can not be subjected to post test cleaning which is necessitated by simulant residue. A simulant meeting these characteristics would also help to ensure its free use and ease of availability.

3.3 Physically Accurate Simulation

The simulant must exhibit acceptable comparison characteristics in terms of flow, discharge, mixing, leakage, stratification, etc. Related characteristics that may also prove important are; liquid/vapor densities and two phase flow profiles, experienced throughout the discharge piping network. Determination of the acceptable sensitivity thresholds for each of these characteristics can only be determined by verification tests.

3.4 Inexpensive

The simulant should be inexpensive and readily available. Slightly higher per pound costs may be offset if lower simulant concentrations can be used, as verified by testing. Lower simulant concentrations would also impact the labor cost by requiring fewer gas cylinders to be moved throughout a ship. The net effect would then be lower overall test costs.

3.5 Easily Detectable

An ideal simulant should be easily detectable with rugged, compact, and off the shelf gas concentration measuring devices (preferably with existing Halon 1301 concentration analyzers). This would facilitate easier transport and set-up at each individual ship. Off the shelf availability is also important because it eliminates the need

for special equipment. Many times specially made equipment can be very expensive and delicate.

4.0 CANDIDATE SIMULANTS

Sulfurhexafluoride (SF_6) has been identified as a possible Halon 1301 simulant. SF_6 possesses similar chemical and physical properties to Halon 1301 as can been seen in Table 1 [8,13,14]. It is chemically inert, non-toxic and is not suspected of contributing to ozone depletion [13,14,15,16].

Chlorodifluoromethane (R-22) is currently under development as a Halon 1301 simulant. Its chemical and physical properties are also presented in Table 1 [17,18]. It is not as close as SF_6 to Halon 1301, especially in molecular weight, critical pressure, and vapor density. It is presently not included in the international protocol signed in September 1987.

Both of these candidates are carried forward through testing. They are to be evaluated based on leakage rates, initial mixing, and pipe network hydraulics.

5.0 LEAKAGE, MIXING AND DISCHARGE TESTS

5.1 Purpose

The tests reported here evaluate sulfurhexafluoride (SF_6) and chlorodifluoromethane (R-22), as simulants for

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Table 1 - Chemical & Physical Properties

	HALON 1301	SULFURHEXAFLOURIDE	R-22
Chemical Formula	$CBrF_3$	SF_6	$CHClF_2$
Molecular Weight	148.91	146.05	86.48
Normal Boiling Point	-57.8°C(-72°F)	-50.8°C(-59.4°F)*	-40.75°C(-41.36°F)
Vapor Pressure at 21°C(70°F)	1.47MPa(213.7psia)	2.16 MPa(312.7psia)	0.94MPa(136.12psia)
Critical Temp	67°C(152.6°F)	45.55°C(114.6°F)	96°C(204.81°F)
Critical Pressure	3.965MPa(575.0psia)	3.759MPa(544.3psia)	4.977MPa(721.91psia)
Liquid Density at 21°C(70°F)	$1567kg/m^3(97.81lbm/ft^3)$	$1378kg/m^3(86\ lbm/ft^3)$	$1209kg/m^3(75.5lbm/ft^3)$
Vapor Density at 21°C(70°F) and .10MPa(14.7psia)	$6.26kg/m^3(0.391lbm/ft^3)$	$6.12kg/m^3(.382lbm/ft^3)$	$3.64kg/m^3(.227lbm/ft^3)$
Liquid Viscosity at 21°C(70°F)	$.0001\frac{Nsec(.0013lbm)}{m^2}$ in sec	$.00029\frac{Nsec(.0023lbm)}{m^2}$ in sec	$.0002\frac{Nsec(.0016lbm)}{m^2}$ in sec
Vapor Viscosity at 21°C(70°F) and .10MPa(14.7psia)	$.00001\frac{Nsec(.00013lbm)}{m^2}$ in sec	$.000015\frac{Nsec(.00012lbm)}{m^2}$ in sec	$.000013\frac{Nsec(.00010lbm)}{m^2}$ in sec
Thermal Conductivity of Vapor at 21°C(70°F) + .101MPa(14.7psia) air .0255W/m°K(.0147Btu)/hrft°F	$.0092W/m°K\frac{(.0053Btu)}{hrft°F}$	$.0142W/m°K\frac{(.0082Btu)}{hrft°F}$	$.0105W/m°K\frac{(.006Btu)}{hrft°F}$
Enthalpy of Vaporization at Boiling Point	$17,700\frac{kJ(7,607Btu)}{kgmole\ lbmole}$	$18,840\frac{kJ(8,100\ Btu)*}{kgmole\ lbmole}$	$20,220\frac{kJ(8,693Btu)}{kgmole\ lbmole}$
at 21°C(70°F)	$12,310\frac{kJ(5,292Btu)}{kgmole\ lbmole}$	$9,630\frac{kJ(4,140Btu)}{kgmole\ lbmole}$	$16,160\frac{kJ(6,948Btu)}{kgmole\ lbmole}$

*Triple Point 0.224 MPa -50.8°C (32.5psia -59.4°F)

Halon 1301 in total flooding system discharge tests. Specifically these tests examine the similarity in mixing, flow discharge from modular cylinders, and leakage dynamics.

5.2 Test Enclosure

These tests were conducted at the Chesapeake Bay Detachment (CBD) of the Naval Research Laboratory, Chesapeake Beach, Maryland. A test enclosure was constructed with nominal inside dimensions of 3.7 m x 3.7 m x 3.7 m (12 ft x 12 ft x 12 ft) providing a floodable volume of approximately 48.9 m^3 (1728 ft^3). The test enclosure has been built using conventional 5.1 x 10.2 cm (2 x 4 in.) framing, with 5.1 x 16.2 cm (2 x 6 in.) floor and ceiling joists. The entire test enclosure is located inside building #244, at CBD. This not only facilitates easier testing but any ambient weather effects are also eliminated. To ensure an air tight environment, two layers of 1.3 cm (.5 in.) painted gypsum wallboard were attached to all interior surfaces. All wallboard joints were then taped and spackeled prior to the application of two coats of water based interior paint. The enclosure was also fitted with a 203 x 91.4 cm (80 x 36 in.) steel door assembly that utilized magnetic seals and two 45.7 x 81.3 x .6 cm (18 x 32 x .25 in.) plexiglass observation windows.

Two, nominally, 20.3 cm (8 in.) ID PVC pipes were inserted through the walls of the enclosure to provide known

leak areas. One pipe was inserted at the top of the back wall. The other was inserted at the bottom of the front wall. Two sets of inserts were made to vary the diameter of both the top and bottom leak. The inserts are nominally 15.24 cm (6 in.) and 6.3 cm (2.5 in.) in diameter. Actual leak diameters are given in Table 2. In some tests, a plexiglass cube 121.9 cm (4 ft) on a side was slipped over the bottom leak to act as a baffle between the leak and the exhaust pipe. This was done to minimize the influence of wind and ambient drafts. A 28.3 m^3/min (1000 CFM) blower unit has been installed to provide rapid post test exhausting.

5.3 Halon 1301 Total Flooding System

The enclosure has been fitted with a roof-mounted modular Halon 1301 total flooding system. A FENWAL Cylindrical Agent Storage Container (P/N 31-192007-251) was utilized in this system. It has an internal volume of .0125 m^3 (.442 ft^3) and is rated for 9.2 Kg (20 lb) to 13.8 Kg (30 lb) of Halon 1301. A manual activation valve was used to initiate the discharge. A discharge pipe from this system penetrates the ceiling at its center and terminates at the nozzle, which is approximately 20.3 cm (8 in.) below the finished ceiling. The discharge pipe has a nominal pipe size of 3.8 cm (1.5 in.) and provides approximately 1.5 m (5 ft) of flow length. The nozzle is a

Table 2 - Leak Diameters

Nominal Diameter	Actual Diameter	Area
20.3 cm (8 in.)	20.8 cm (8.1875 in.)	340 cm^2 (52.6 $in.^2$)
15.24 cm (6 in.)	15.24 cm (6 in.)	182 cm^2 (28.3 $in.^2$)
6.35 cm (2.5 in.)	6.03 cm (2.375 in.)	28.6 cm^2 (4.43 $in.^2$)

Bete (P/N TF48FC) Spiral Nozzle. This same system was used for the simulants, SF_6 and R-22.

5.4 Procedure

All tests performed during this phase compare Halon 1301 and the simulants at concentrations of 5% by volume. The leakage area was varied with a test of each gas at a specified leakage area. The top and bottom leaks were the same size.

5.4.1 Test Sequence

A. Discharge bottle was filled with desired agent and super-pressurized with nitrogen to 350 psig.

B. Data logging was initiated and discharge started.

C. 30 s after discharge, the bottom leak was opened. (In initial tests, this time period was approximately 10 min).

D. 15 min. after discharge, the top leak was opened. (In initial tests, this time period was approximately 20 min).

E. Test ended when the concentration had fallen to half its maximum four feet from the floor or 1.5 hours after discharge.

F. Room was purged with exhaust blower.

5.4.2 Smoke Test

Smoke was used on 5 tests in order to visualize the flow of agent out of the room and the development of an interface. In these tests, the enclosure was filled with smoke prior to discharge.

In the first three tests, dime store smoke bombs were used in increasing quantity. After this failed to sufficiently visualize the flow, a military type smoke grenade was used for the other two tests.

5.5 Instrumentation

The location of instrumentation in the test enclosure is shown in figures 1 and 2.

5.5.1 Halon 1301 Analyzers

Halon 1301 concentrations, as well as simulant concentrations, were monitored by six thermal conductivity analyzers (three Perco Halon Analyzers and three TUURE Halon Analyzers). Each of these provide three sampling points for a total of 18, however, only 17 were used. All analyzers are located remotely from the space, with .16 cm (.25 in.) Tygon tubing transiting to the desired sampling points. Actual sampling points are arranged as shown in Figures 1 and 2, with the following breakdown:
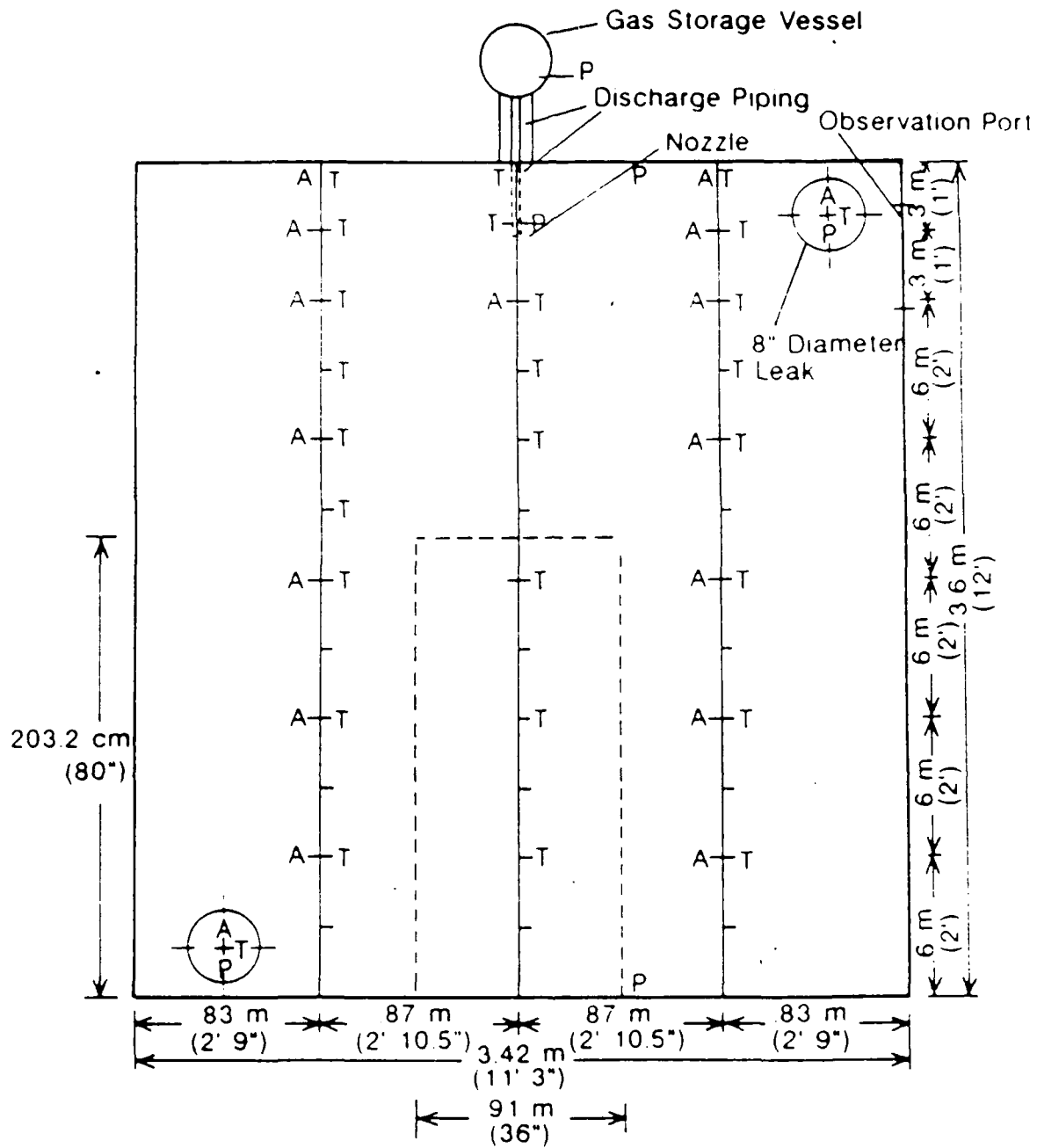
A · Gas Analysis Position

T · Thermocouple Location

P · Pressure Transducer Location

Fig. 1 · Vertical profile of Halon 1301 simulant enclosure

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8" Diameter Leak

ATP

Observation Ports

127 cm (5")

17 m (5' 7")

3.42 m (11' 3")

P + T
A + T   A + T

.76 m (2' 6")

A + T

.83 m (2' 9")

Door

ATP   P

| .83 m (2' 9") | .87 m (2' 10.5") | .87 m (2' 10.5") | .83 m (2' 9") |

3.42 m (11' 3")
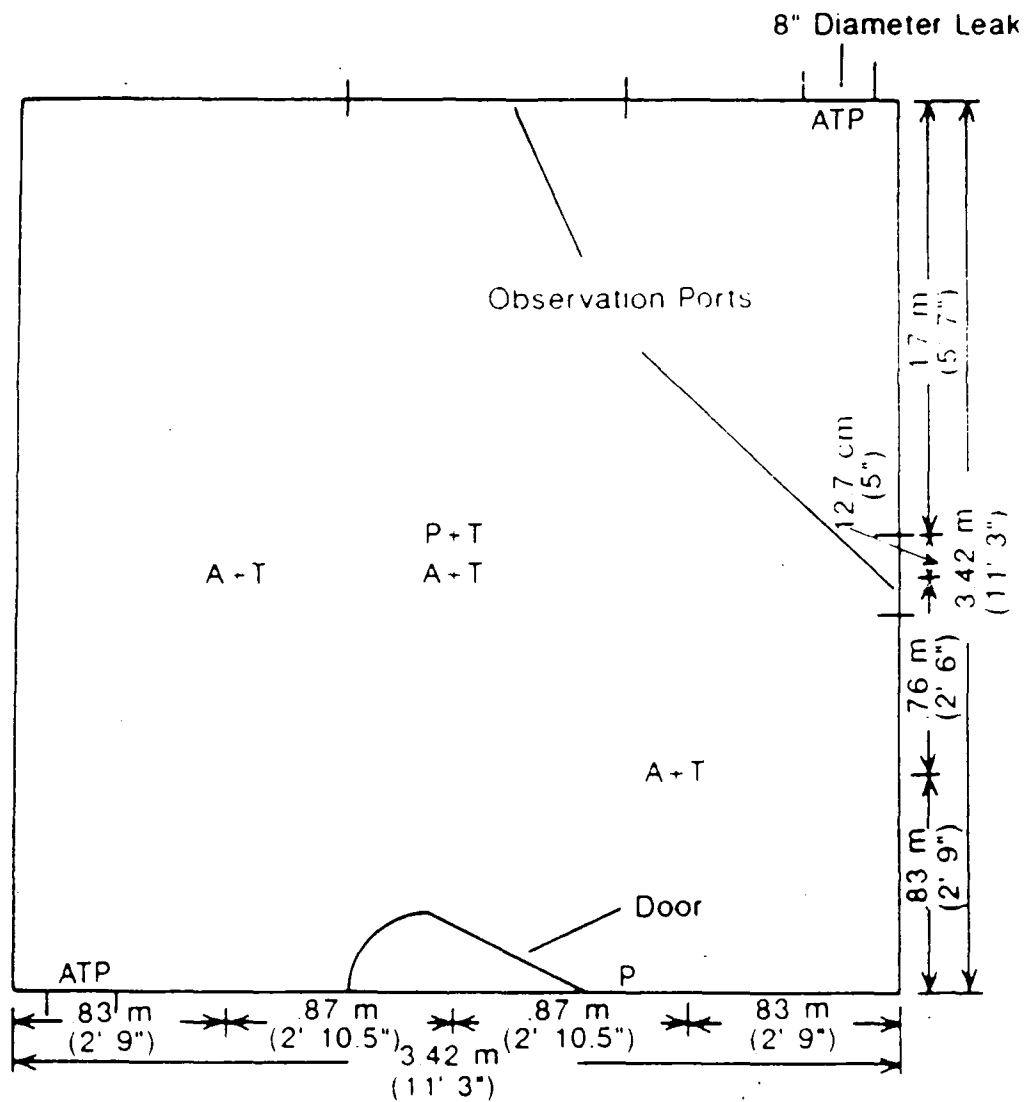
A - Gas Analysis Position

T - Thermocouple Location

P - Pressure Transducer Location

Fig. 2   Horizontal cross-section Halon 1301 simulant enclosure

- 14 sampling points distributed on two vertical tiers
  with .6 m (2 ft) intervals between sampling points
  except at the ceiling where the first two intervals
  are .3 m (1 ft);
- One sampling point in the center of the room, .3 m
  (1 ft) below the discharge nozzle; and
- Two sampling points were used to measure the
  concentrations at the leaks, one at each leak.

During tests using smoke, the analyzers were protected with
filters or their tubes were capped and the analyzer turned
off.

5.5.2 Temperature

The compartment temperature was recorded by 30 Inconel
sheathed thermocouples arranged as follows:
- 24 distributed on three vertical tiers with .6 m (2
  ft) intervals except at the ceiling where the first ≤
  intervals are .3 m (1 ft);
- 1 inserted in the discharge piping directly preceding
  the nozzle;
- One at each leak; and
- Three were distributed vertically outside the
  enclosure to provide a reference temperature profile.

5.5.3 Pressure

Pressure was monitored in seven locations. Two 0 to 6.9 MPag (0 to 1000 psig) Genisco Technology Corp. Model SP500 pressure transducers were used to monitor the gas storage pressure and the system nozzle pressure. In addition six low range pressure transducers, three Celesco Transducer Products Model LCVR/LCCD 0-2 cm (0-0.75 in.) water column transducer and three Schaevitz Engineering Model 3091 0-5 cm (0-2 in.) water column transducers, were used. Two were used to measure the pressure at the leak, one at each leak. Three low range pressure transducers were arranged evenly on a vertical tier to record the differential pressure between the test enclosure and the surrounding atmosphere. The remaining low range pressure transducer duplicated the center position in the vertical tier.

5.5.4 Video Recording

During all tests the characteristics of the nozzle discharge was recorded on video tape. In the tests using smoke, the flow out of the lower leak, and the descending smoke level were also recorded.

5.6 Results and Analysis

The results and analysis of these tests are broken into the four main aspects of a total flooding system: leakage, flow hydraulics, mixing, and stratification. In these tests

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leakage is of the greatest importance due to the relative simplicity of the test facilities.

5.6.1 Leakage Analysis

The flow of a vapor mixture out of an enclosure is essentially one of natural convection. The flow is driven by the density difference between the mixture and the surrounding air. Air enters the enclosure at the same volumetric flow rate as the mixture leaving.

In an enclosure with one opening both the air and the mixture must flow through the same opening. The flow is extremely slow as the incoming air must fight its way through the denser mixture to reach the top of the enclosure. A high degree of mixing occurs as air flows into the enclosure, resulting in no real air layer at the top of the enclosure.

This situation can be modeled using the neutral plane concepts of Yao and Smith [19]. A neutral plane is defined as the horizontal plane where there is no pressure difference (and therefore no flow) between the inside and outside of the enclosure. As the flow rates are small, the pressure difference, ΔP, can be found from

$$\Delta P = gy(p_m - p_{air})$$

where y is distance from the neutral plane, g is the acceleration due to gravity, p_m is the density of the vapor mixture and p_{air} is the density of the surrounding air. The velocity of the air entering at a plane above the neutral

plane, V_{air}, and velocity of the vapor mixture leaving at a plane below the neutral plane, V_m, can be determined from the Bernoulli equation [10]:

$$V_{air} = [2gy\ (p_m-p_{air})/p_{air}]^{0.5}$$

$$V_m = [2gy\ (p_m-p_{air})/p_m]^{0.5}$$

The volume flow rate of the mixture out of the enclosure is then found by integrating the velocity of the mixture over the area below the neutral plane

$$Q_m = K_d \int V_m dA$$

where Q_m is the volume flow rate, and K_d is the discharge coefficient.

As the density of the mixture near the leak is essentially constant, the volume flow rate is also constant.

In an enclosure with two openings, the air will flow in through the upper opening while the heavier mixture flows out through the lower opening. The separation of the two flows and the low flow rate keep the two fluids from mixing to any significant degree. This makes the flow a descending interphase phenomenon.

The model used for two openings differ from that for one opening in that the variation of the velocity across either opening is unimportant and the volume flow rate is not constant.

The volume flow rate of the vapor mixture out of the enclosure is determined from the following equation:

$$Q = K_d A\ [2g(h/K_1)(p_m - p_{air})/p_m]^{0.5}/[1. - (A/A_r)^2]^{0.5}$$

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where Q is the volume flow rate, h is the height of the
interphase which is measured from the midpoint of the lower
opening to the interphase, A is the cross-sectional area of
the lower opening, A_r is the horizontal cross-sectional area
of the room, and K_d is the discharge coefficient for this
flow. The constant, K_1, relates the height of the interphase
to that of the nuetral plane and is determined as follows:

$$K_1 = 1.+[K_d A/(K_{d2} A_2)]^2 (p_{air}/p_m)$$

where K_{d2} is the discharge coefficient of the flow of air
into the room and A_2 is the cross-sectional area of the upper
opening. The flow rate is at its maximum value initially and
decays as the interphase descends.

When the plexiglass cube is placed over the leak, the
discharge coefficient, K_d, is reduced due to the resistance
of flow through the cube. This effect can be modeled as
follows:

$$K_d = K_d'[K_3/(K_2 + K_3)]^{0.5}$$

where K_d is the reduced discharge coefficient, K_d' is the
discharge coefficient without the cube, and K_2 and K_3 are
determined as follows:

$$K_2 = K_d'^2 A^2/[1 - (A/A_r)^2]$$

$$K_3 = K_{d4}^2 A_4^2/[1 - (A_4/A_c)^2]$$

where K_{d4} is the discharge coefficient of the flow out of the
cube, A_4 is the cross-sectional area of the opening in the
cube, and A_c is the vertical cross-sectional area of the
cube. As can be seen from this, the effects of the cube

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increases as K_2 increases relative to K_3.

This model lead to a differential equation that can be solved for the time required for the interphase to descend to a given level. The resulting equation is:

$$t = 2A_r(h_i^{0.5} - h^{0.5})/(1 - (A/A_r)^2)^{0.5})$$
$$/[K_dA[2g(p_m - p_{air})/(K_1 p_m)]^{0.5}]$$

where h_i is the initial height of the interphase.

The calculation of interface position as a function of time using these equations and comparison with experimental data is given in Appendix A.

5.6.2 Leakage Results

In the experiments performed the lower leak is opened 30 seconds after the discharge is initiated. Sometimes this was longer. A one opening situation exists until the upper leak is opened 14.5 minutes later. As can be seen in Figure 3, the concentration at the ceiling dropped only slightly with only the bottom leak open.

With both leaks open the average concentration in the enclosure, as shown in Figure 4, falls off dramatically. In the analysis of this decay the interphase was taken to be at an analyzer point when the concentration starts to drop. The initial height of the interphase was taken as one foot below the ceiling and 3.2m (10.5 ft) above the center-line of the lower opening). The discharge coefficients were determined by comparison with experimental data. They were found to be
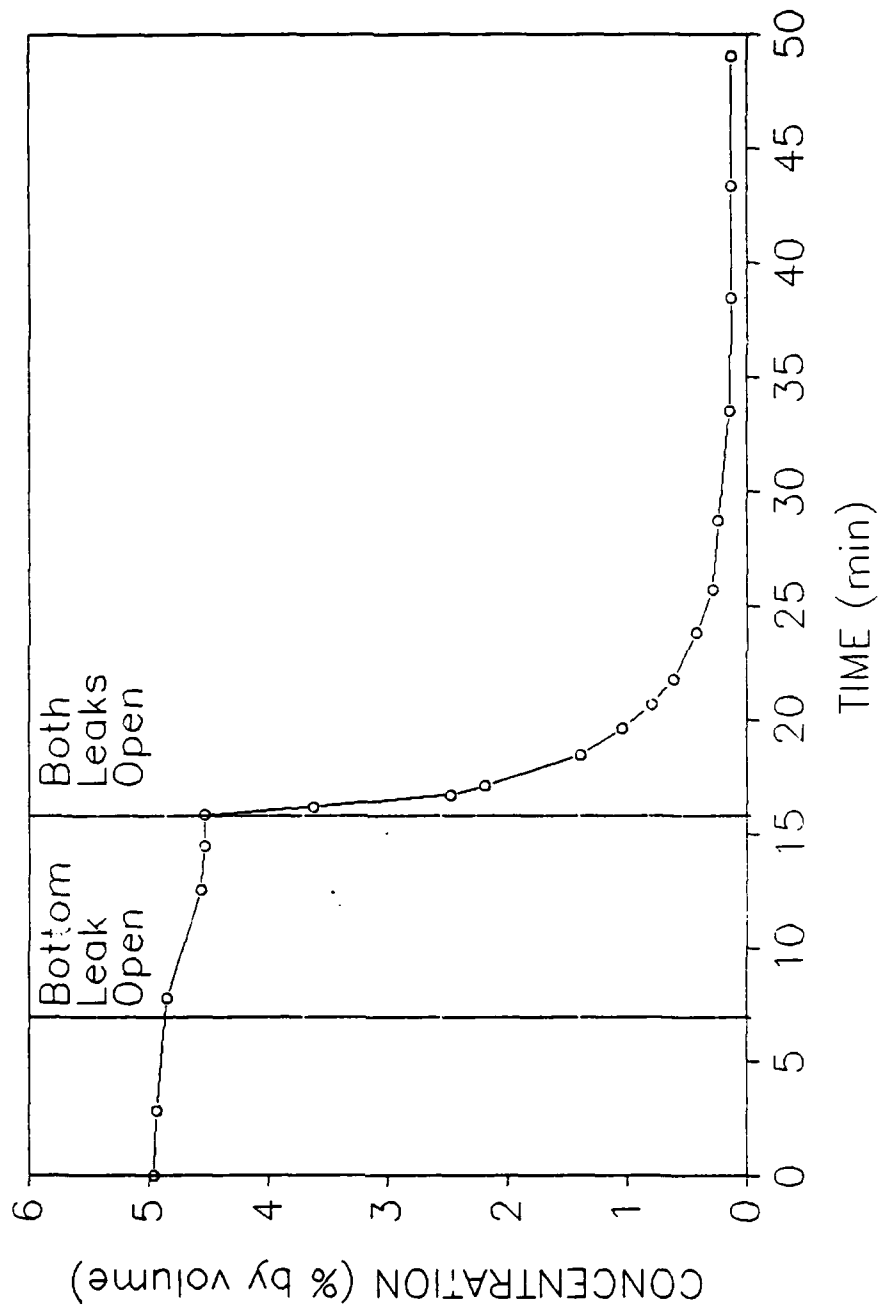
Fig. 3 -- Concentration at the ceiling

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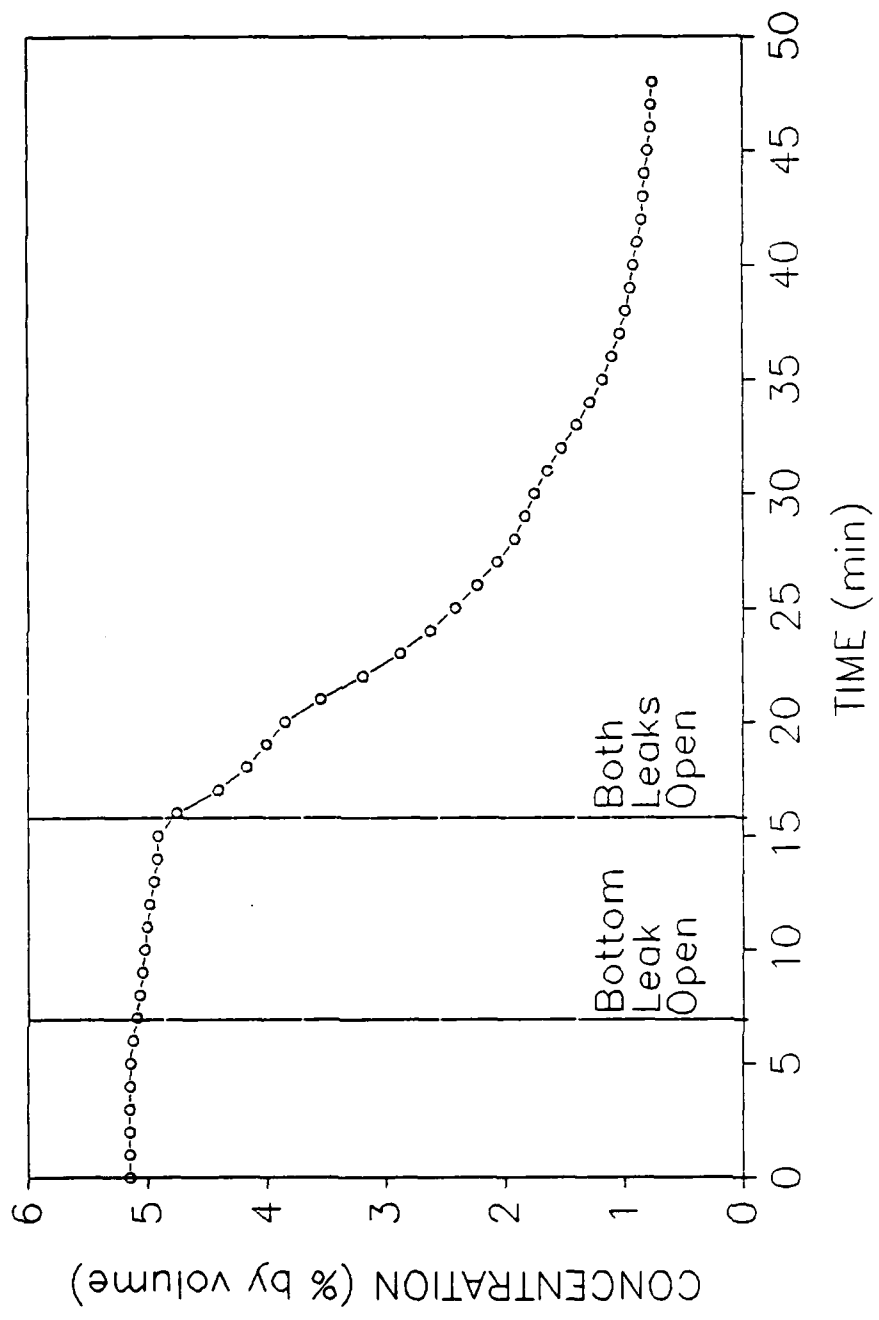
Fig. 4 — Average concentration in the enclosure — 20.8 cm (8 in) leaks

0.82 for all leak sizes. The discharge coefficient for flow through the mixing cube was lower, 0.46, due to a baffle plate in front of the opening.

Figures 5-7, show the average density, average concentration and the interphase height with both leaks open. Figures labeled with an a or b represent testing done with 15.24 cm (6 in.) and 6.cm (2.5 in.) leaks, respectively. The data shown in these figures was normalized to represent the same initial concentration of 5% by volume. This was done to eliminate the effect of slightly different initial concentrations.

This was done as follows:

$$t = t'([(p_m' - p_{air})/(K_1'p_m')]/[(p_m - p_{air})/(K_1 p_m)]^{0.5}$$

where the t' is the observed time, p_m' is the observed density, K_1' is based on the observed density, t is the normalized time, P_m is the density of a 5% by volume mixture, and K_1 is based on the density of a 5% by volume mixture. The maximum adjustment was a decrease of 1 min. at the last interphase height taken.

It can be seen from the experimental data that the agreement between the SF_6 and Halon 1301 leakage rates is very good. The largest difference between SF_6 and Halon 1301 in time for the interphase to descend is the 3 min difference evidenced at the 2.3 m (7.5 ft) level for 6 cm (2.5 in.) leaks (Fig. 7b) and is a relative difference of 10%. R-22, as expected, has a much slower leakage rate than Halon 1301.
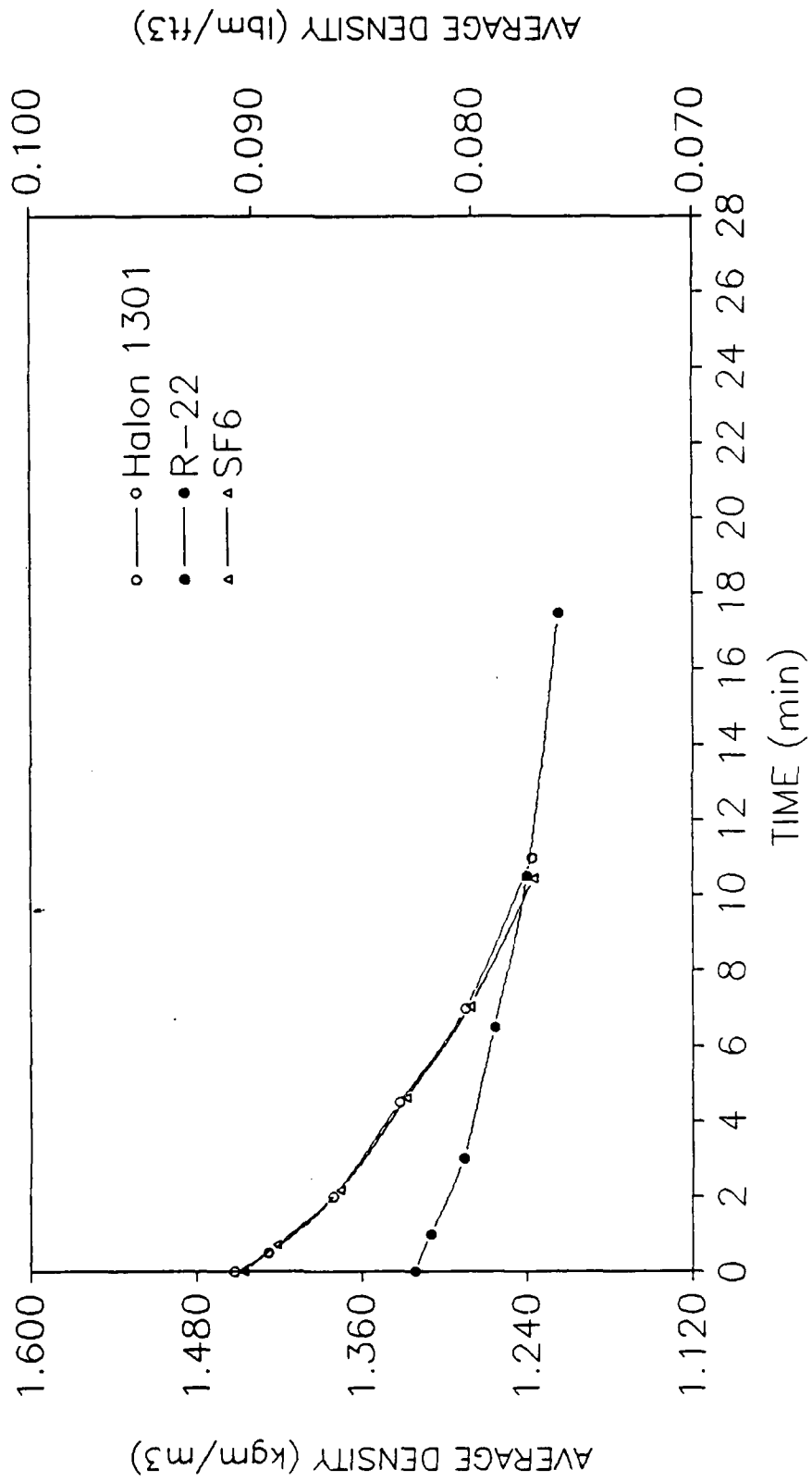
Fig. 5 — Experimental average density for 20.8 cm (8 in) leak
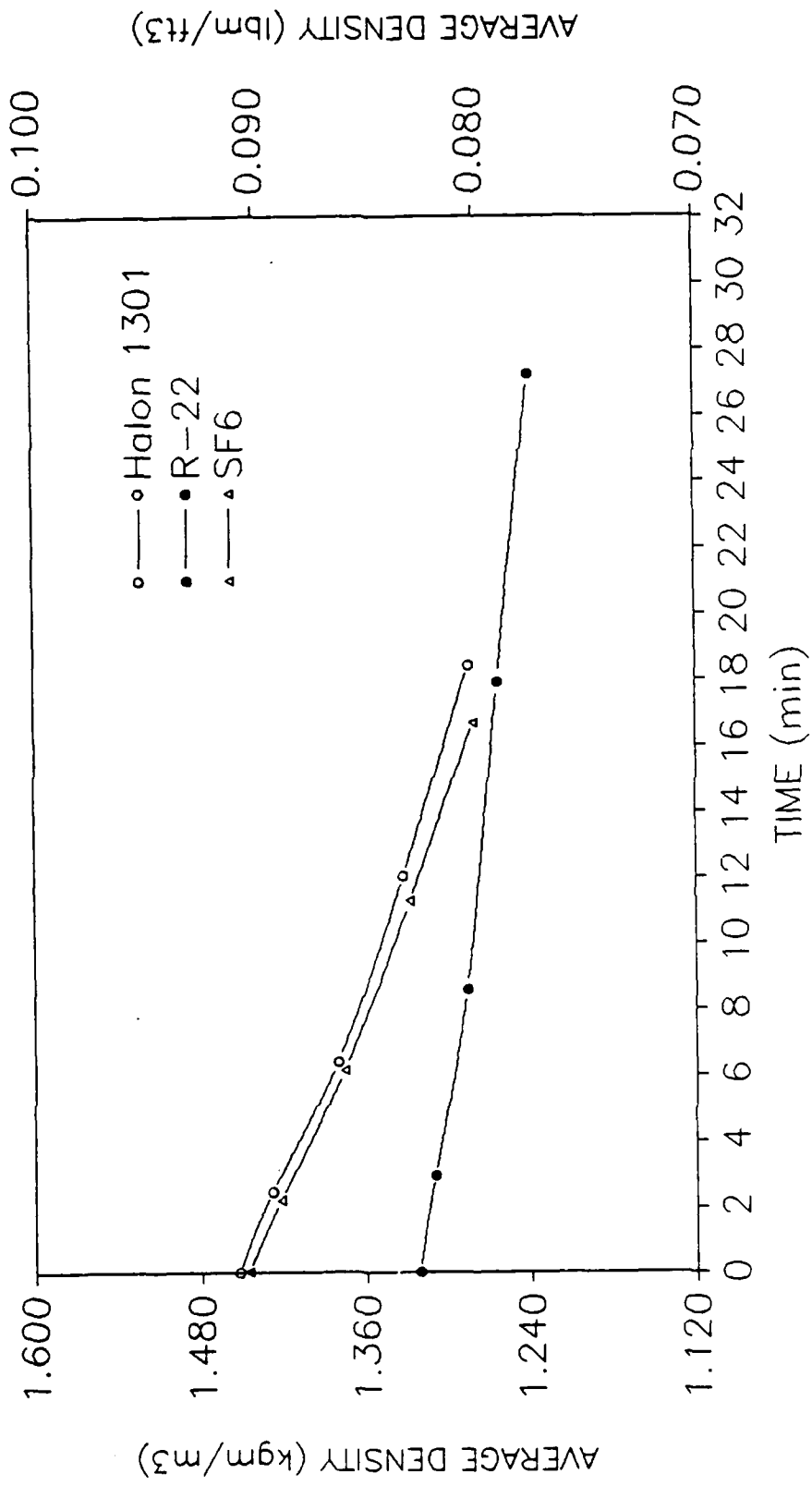
Fig. 5a – Experimental average density for 15.24 cm (6 in) leaks

Fig. 5b – Experimental average density for 6 cm (2.5 in) leaks

AVERAGE DENSITY (lbm/ft3)

AVERAGE DENSITY (kgm/m3)

TIME (min)

o Halon 1301
• R-22
△ SF6
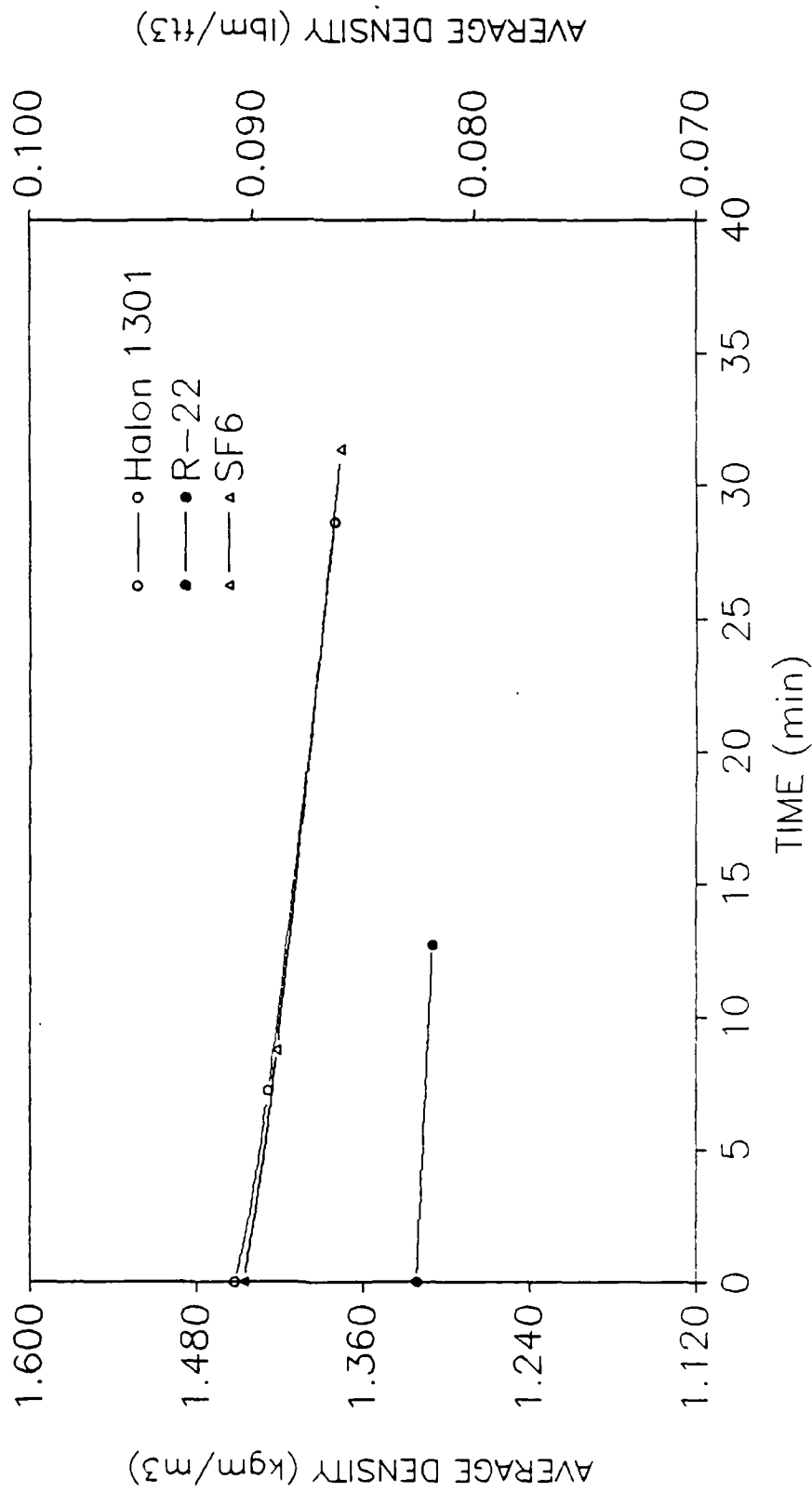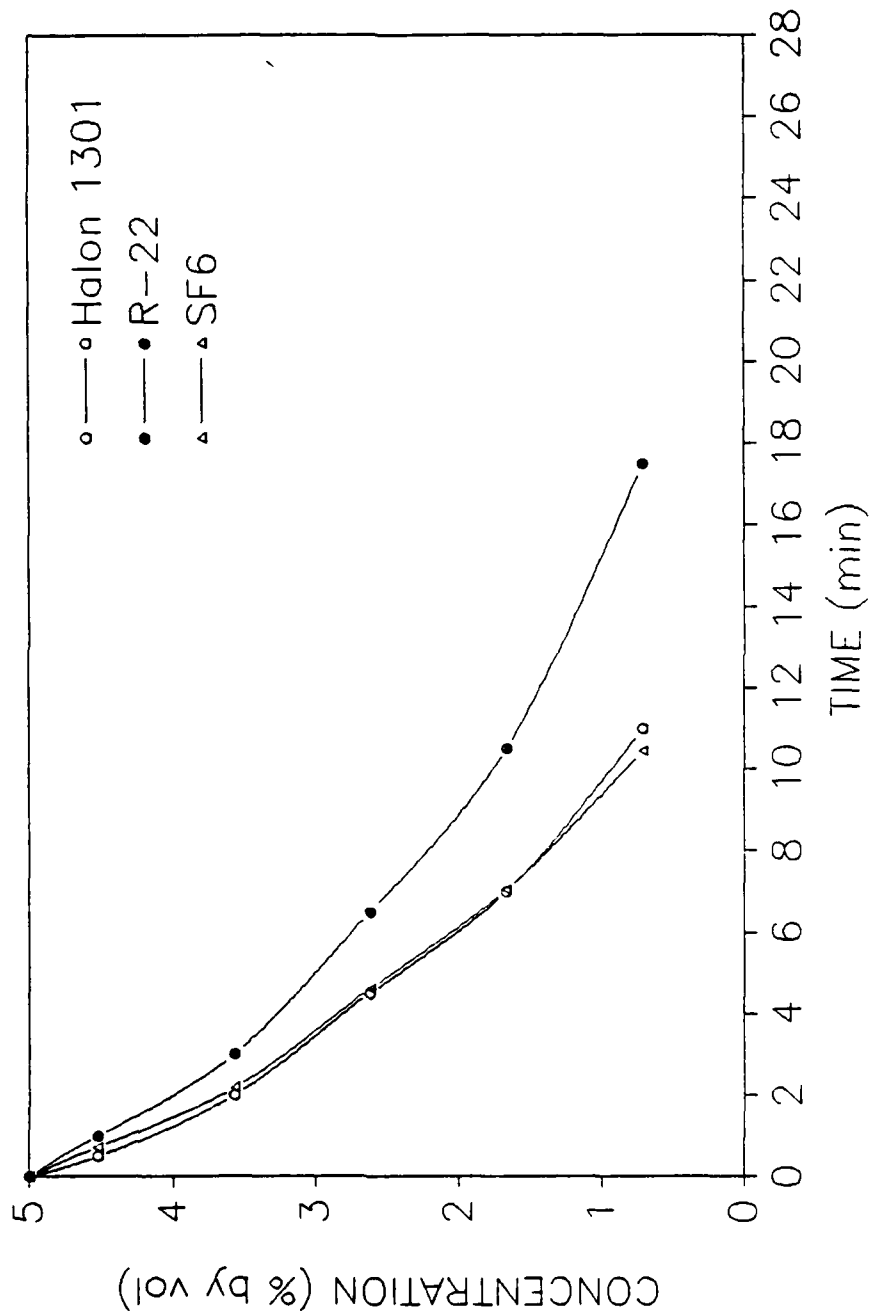
Fig. 6 – Experimental average concentration
for 20.80 cm (8 in) leak
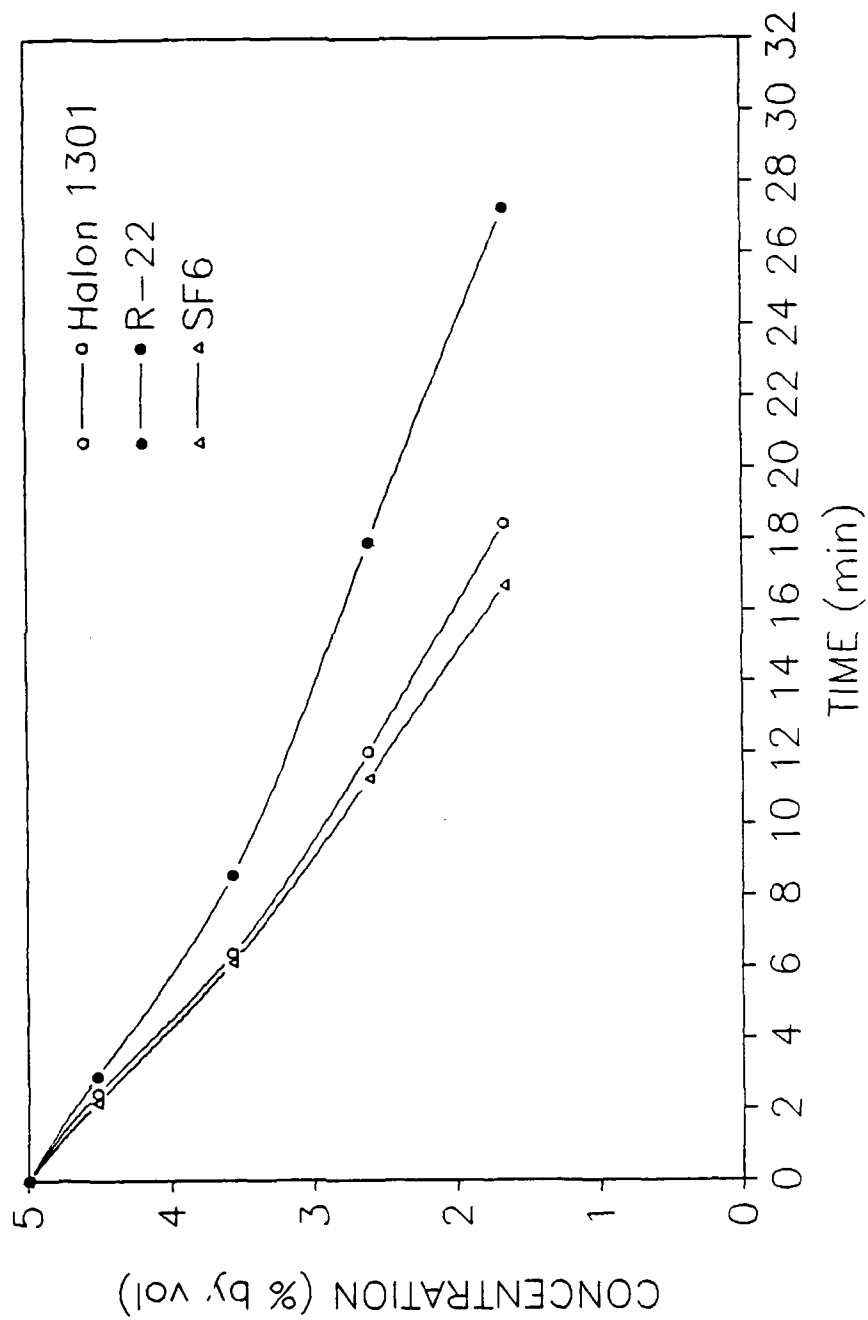
Fig. 6a – Experimental average concentration
for 15.24 cm (6 in) leaks
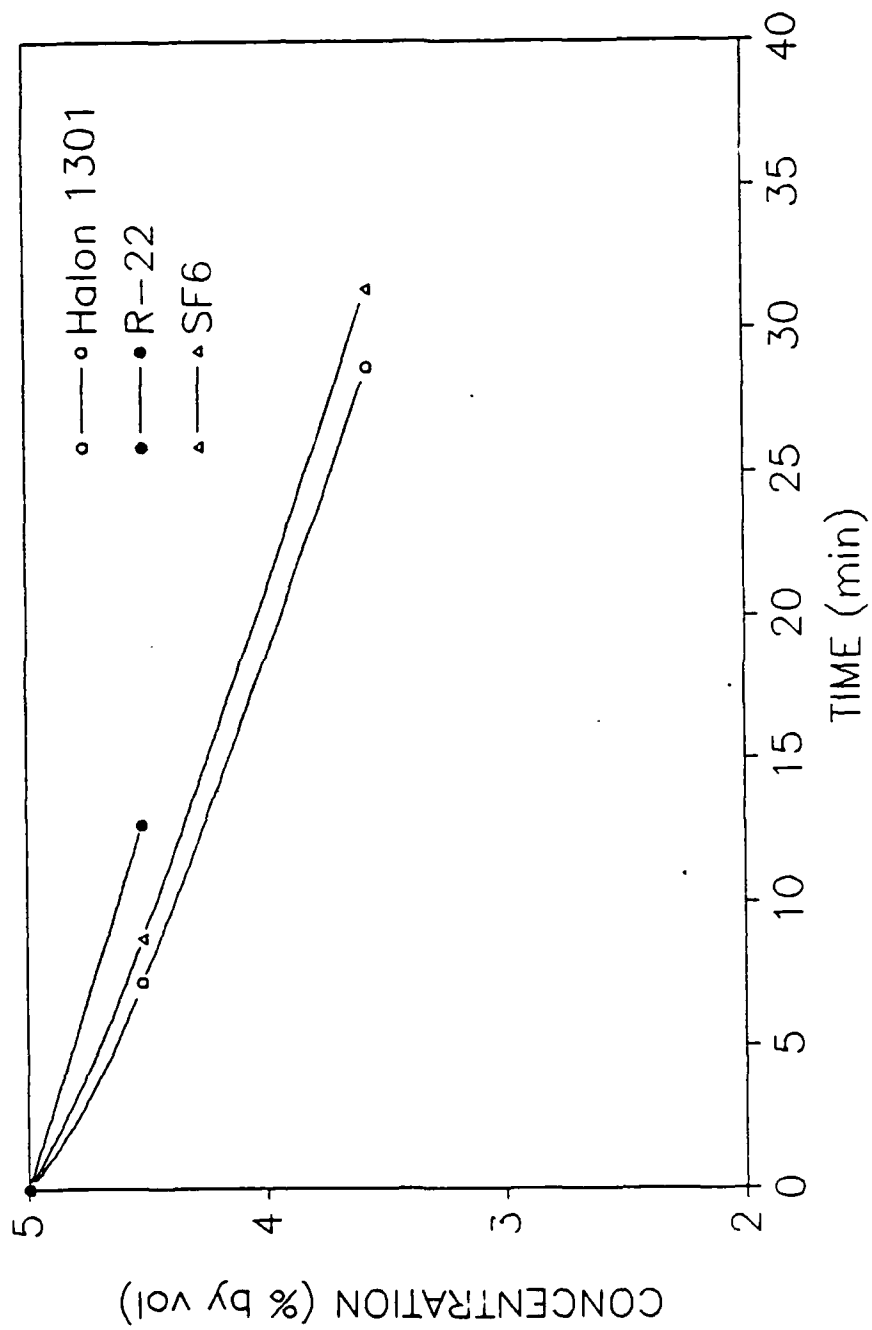
Fig. 6b – Experimental average concentration for 6 cm (2.5 in) leaks
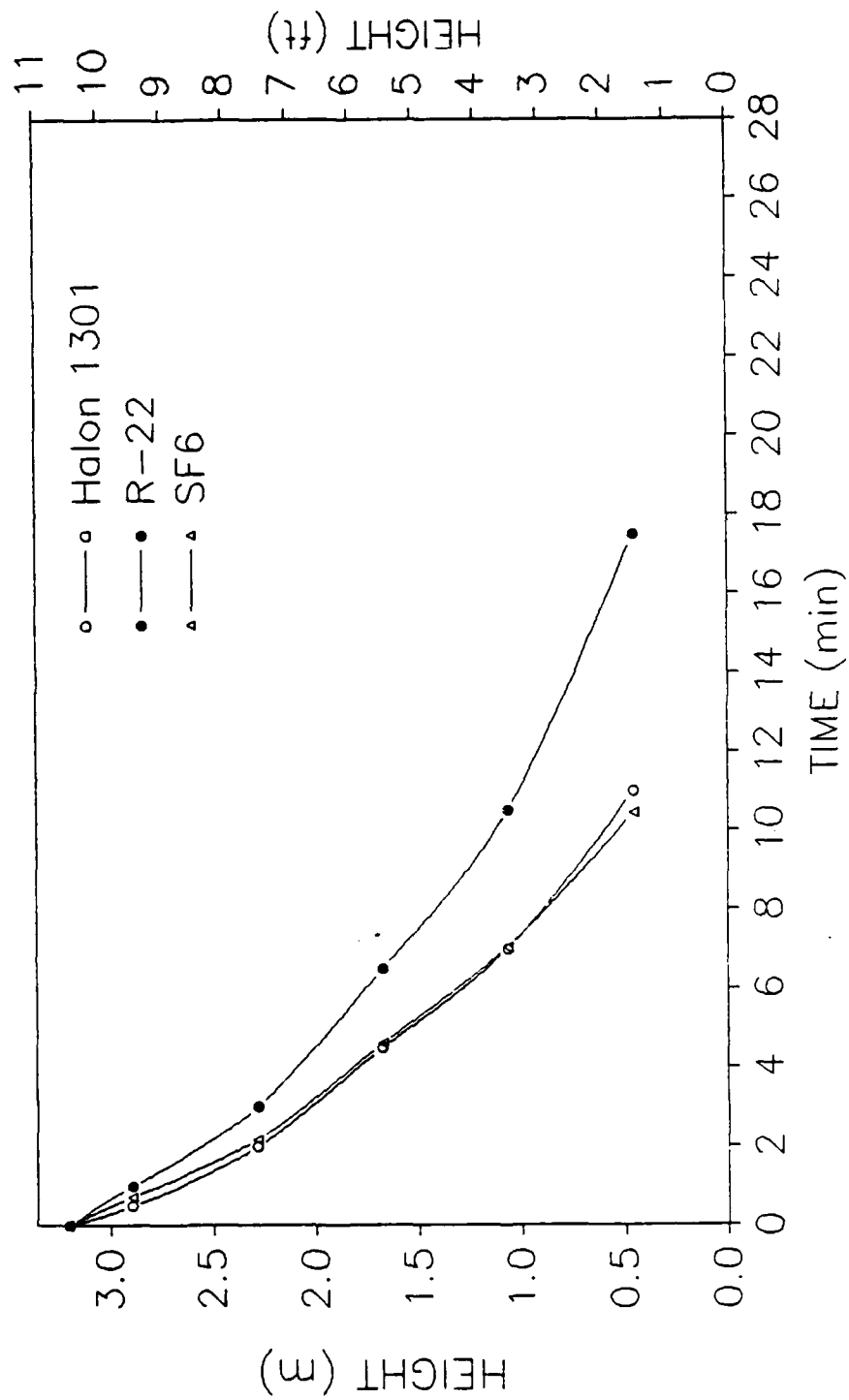
Fig. 7 – Experimental interphase height for 20.8 cm (8 in) leaks
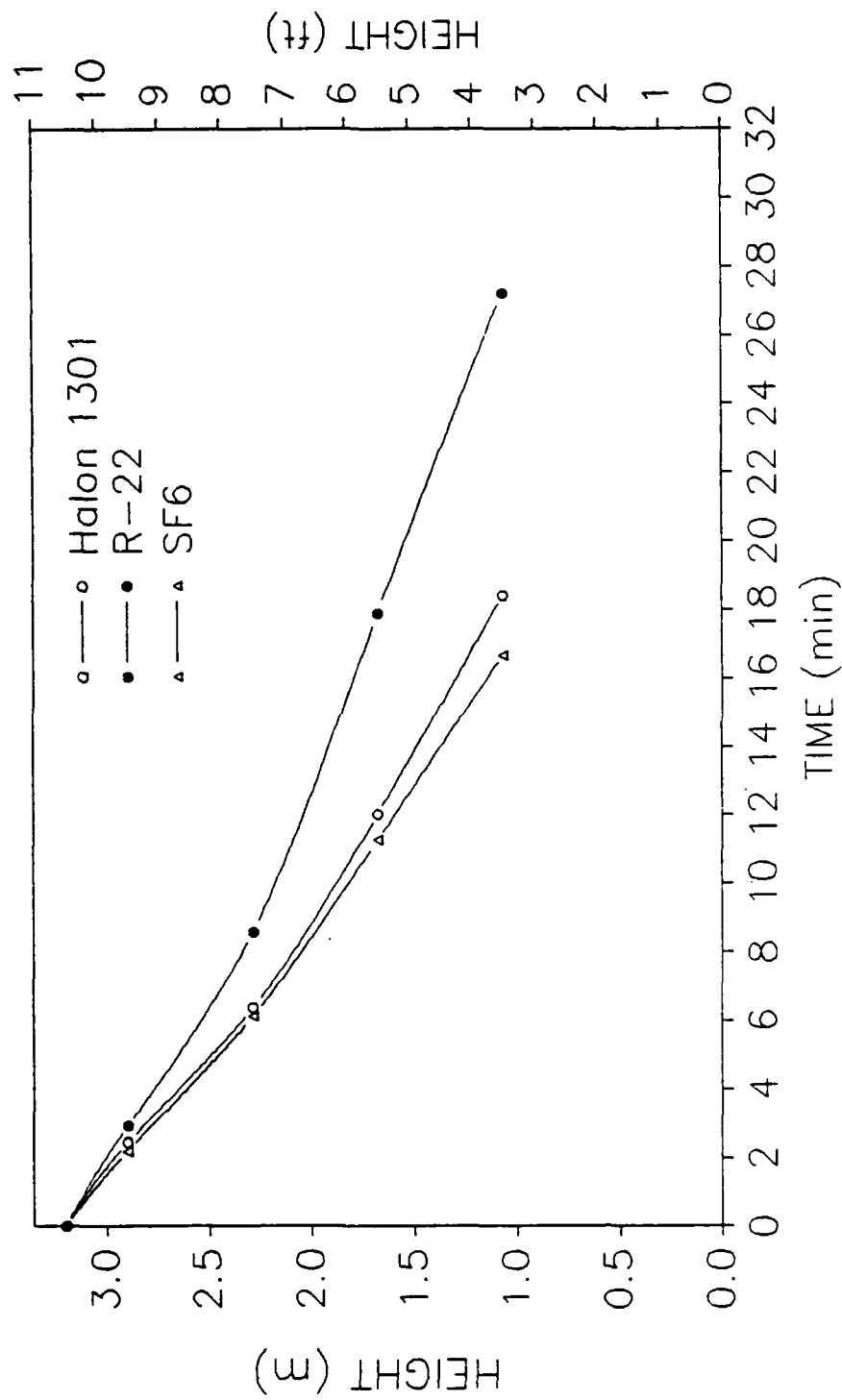
Fig. 7a – Experimental interphase height for 15.24 cm (6 in) leaks
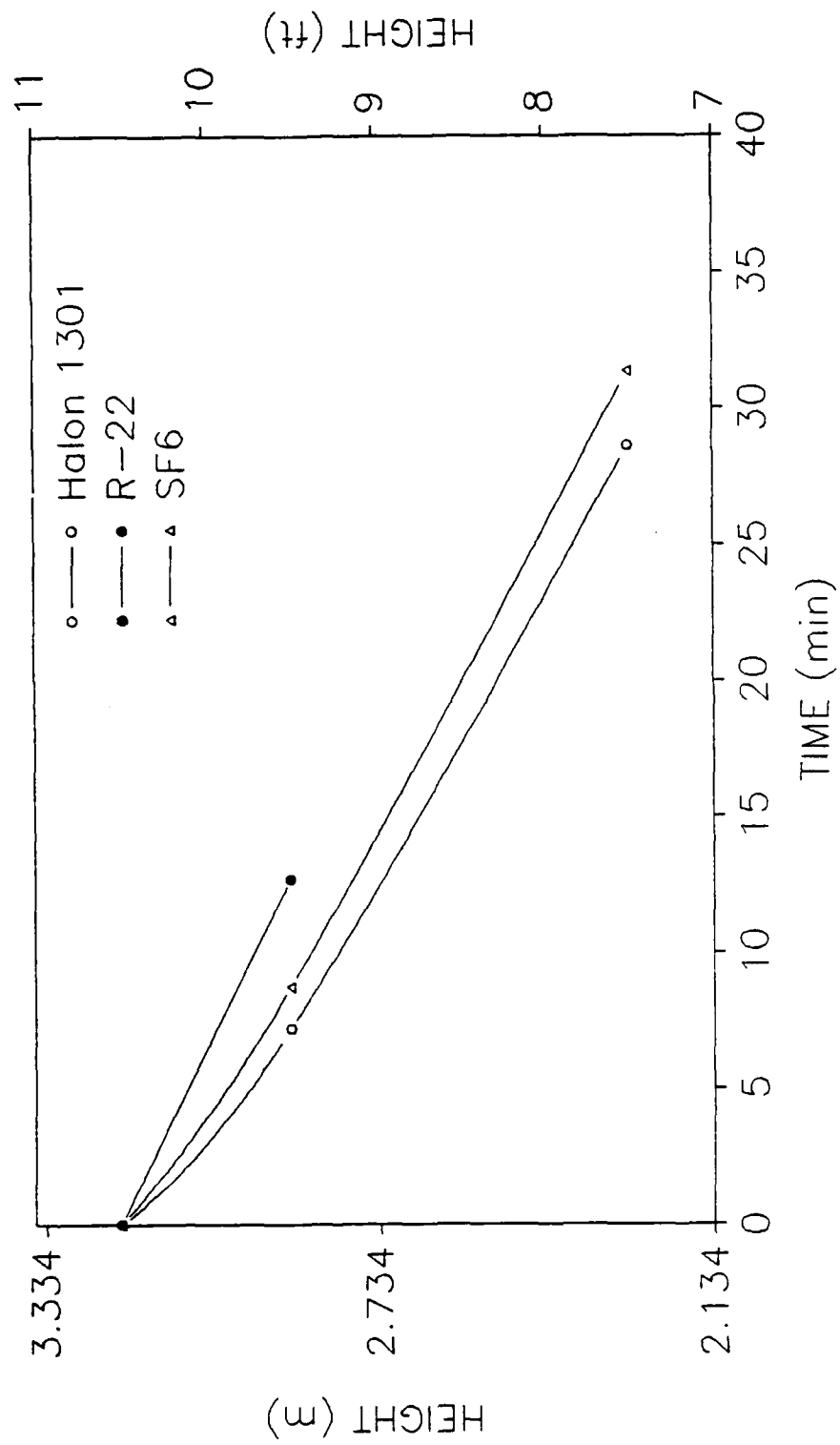
Fig. 7b – Experimental interphase height for 6 cm (2.5 in) leaks

The R-22 interphase takes nearly 50% more time to descend.

5.6.3 Flow Hydraulics

The piping system used during these tests is simple and represents a modular system. It only has approximately 1.5 m (5 ft) of flow path, with two valves and a nozzle. Both candidate simulants had bottle pressure recession and nozzle pressure curves similar to those of Halon 1301 as can be seen in figures 8 and 9. Sulfurhexafluoride, with its higher vapor pressure, was as expected, higher than Halon 1301 and similarly, R-22 was lower.

A more thorough study of flow hydraulics is planned.

5.6.4 Mixing and Stratification

Halon 1301 and both candidate simulants had no problem with either mixing or stratification in these tests. In all tests the maximum concentration was achieved almost immediately with no difference between the floor and ceiling.

The test chamber is relatively small, has no obstructions and only a mild temperature gradient, so no difficulty with mixing or stratification was expected.

5.7 Conclusion

These tests have shown that SF_6 has significant promise as a Halon 1301 simulant in total flooding system discharge tests. They have confirmed that SF_6 is an excellent simulant for the 1301 when considering leakage from a compartment.

PRESSURE (psig)

PRESSURE (MPag)

TIME (sec)

Halon 1301
R-22
SF6
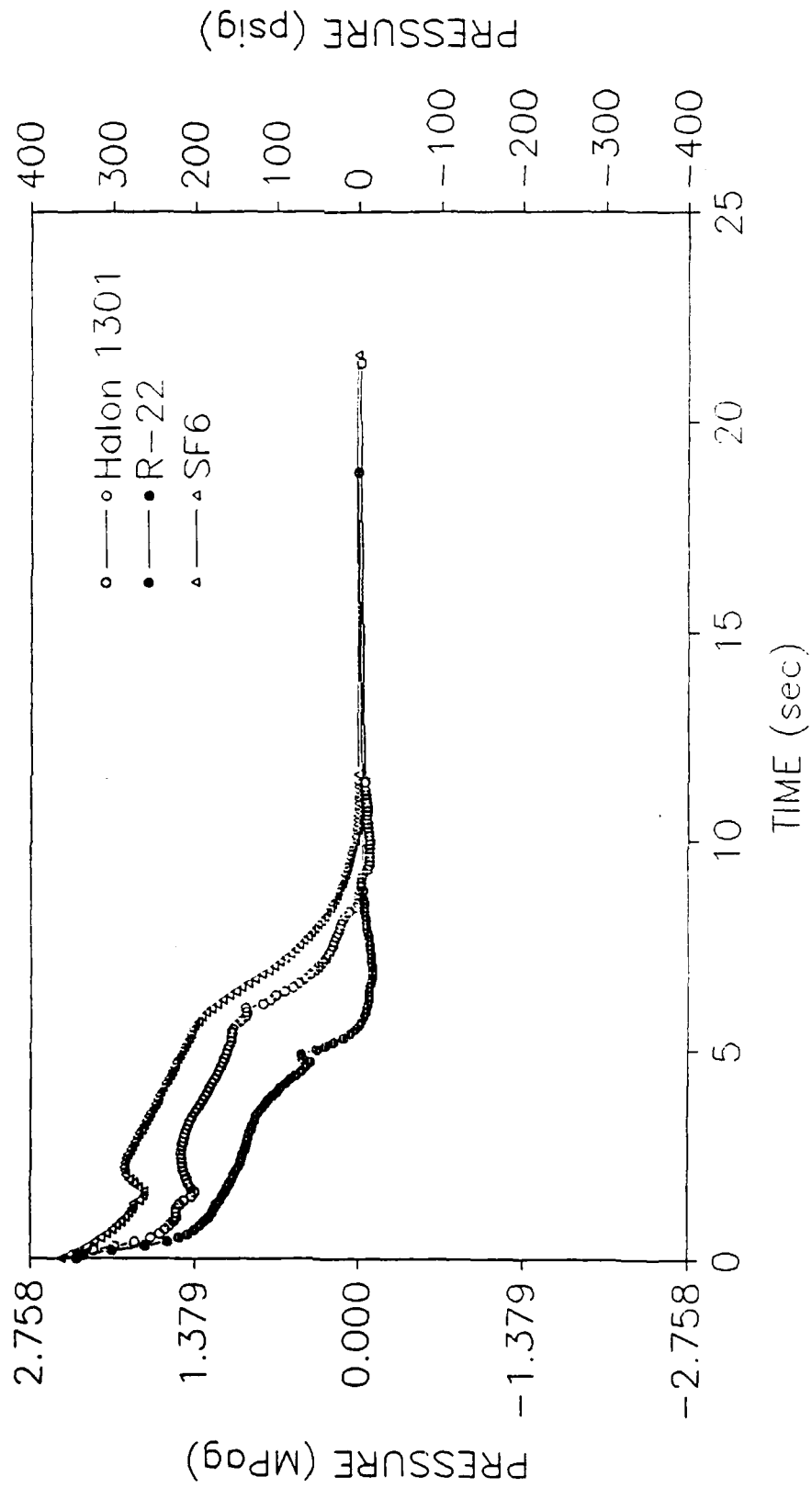
Fig. 8 -- Bottle pressure

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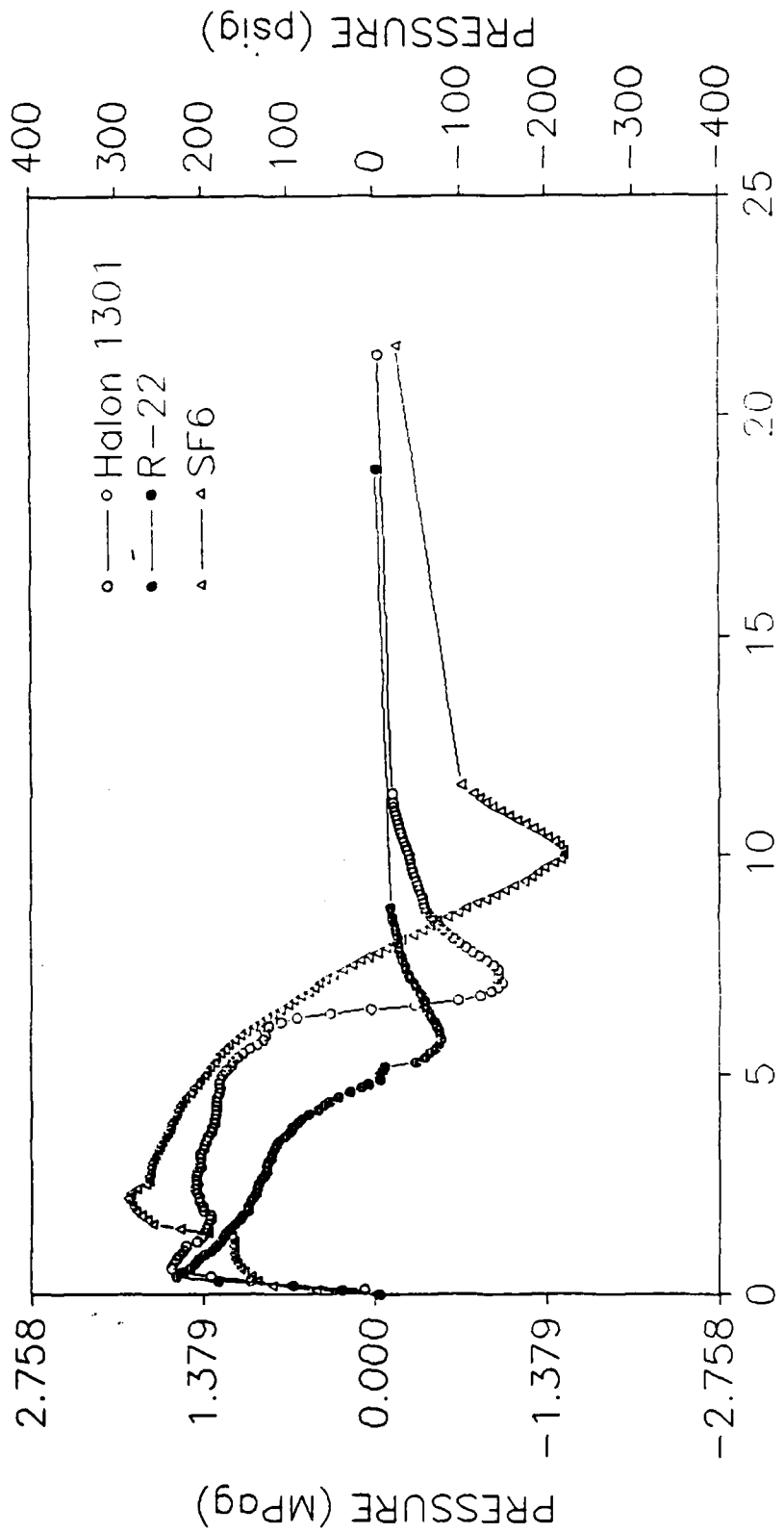
Fig. 9 – Nozzle pressure

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More study is needed and is planned in the areas of flow hydraulics, mixing, and stratification.

6.0 ADDITIONAL TESTING

Additional testing is planned to further examine sulfur hexafluoride (SF_6) and chlorodifluoromethane (R-22) as inert simulants for Halon 1301 (bromotrifluoromethane) in total flooding system discharge tests. Three additional series of tests are planned:

- Modular System Flow
- Initial Gas Mixing
- Complex System Flow

6.1 Modular System Flow

These series tests are designed to look at the flow hydraulics of modular systems. These systems are characterized as single cylinders with short pipes and nozzles. The tests will investigate the effects of fill densities on discharge rates. Fill densities generally vary from 640.7 Kg agent/m^3 (40 lbm agent/ft^3) to 1121 kg agent/m^3 (70 lbm agent/ft^3).

6.2 Initial Gas Mixing

This series will be done in order to investigate the mixing characteristics of Halon 1301 and the two candidate simulants. The nozzle flow which drives the initial mixing

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will be obstructed. The concentration profiles for each simulant and Halon 1301 will be compared.

6.3 Complex System Flow

This series of tests will look at flow hydraulics. This investigation will include balance and unbalanced flow splits as well as differing pipe volumes.

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APPENDIX A

Predicted vs. Experimental Leakage

The equations developed in Section 5.6.1 are used to estimate the halon interface height position as a function of time, in this section. In the experimental data, the actual location of the interphase is difficult to determine. This is due to a combination of diffusion into the air above the mixture and mixing caused by air currents above the mixture. Therefore, two curves for the experimental value are included. In the curve labeled experimental, the interphase is taken where the concentration starts to drop off. In the curve labeled time to ½ conc, the interphase is taken where the concentration has dropped to half its initial value. Figures 10, 11, and 12 compare the experimental and predicted values of the interphase height versus time of Halon 1301, R-22, and SF_6 respectively. Figures labeled with an a or b represent testing done with 15.24 cm (6 in.) and 6 cm (2.5 in.) pipes respectively.

Figures 13 through 15 are the predicted values of the average density, concentration, and interphase height. Each of these is plotted against time for Halon 1301, SF_6, and R-22.

Figures 16 through 18 are the normalized experimental values with the interphase taken at the half initial concentration point.
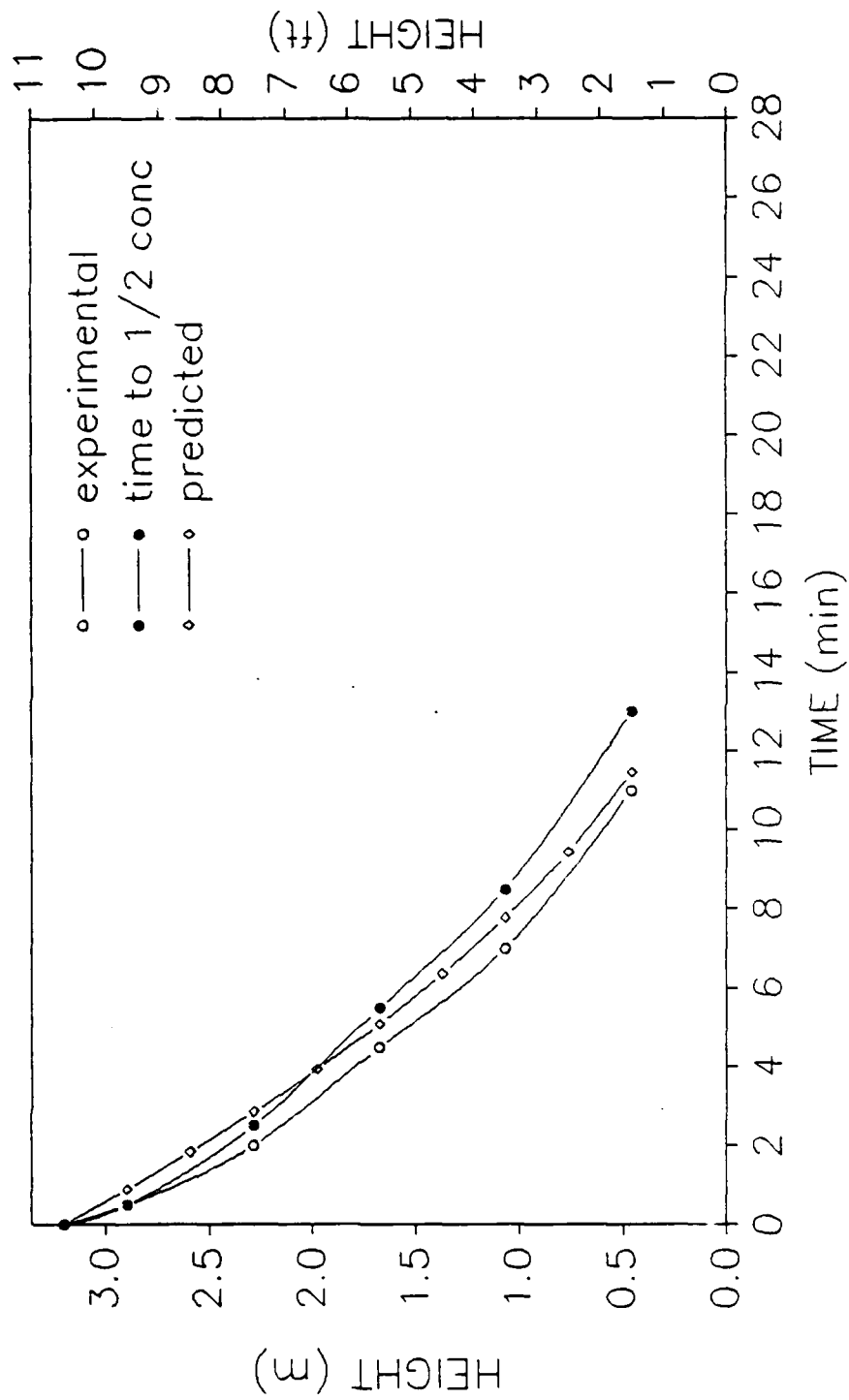
Fig. 10 — Interphase height comparison for Halon 1301 — 20.8 cm (8 in) leak
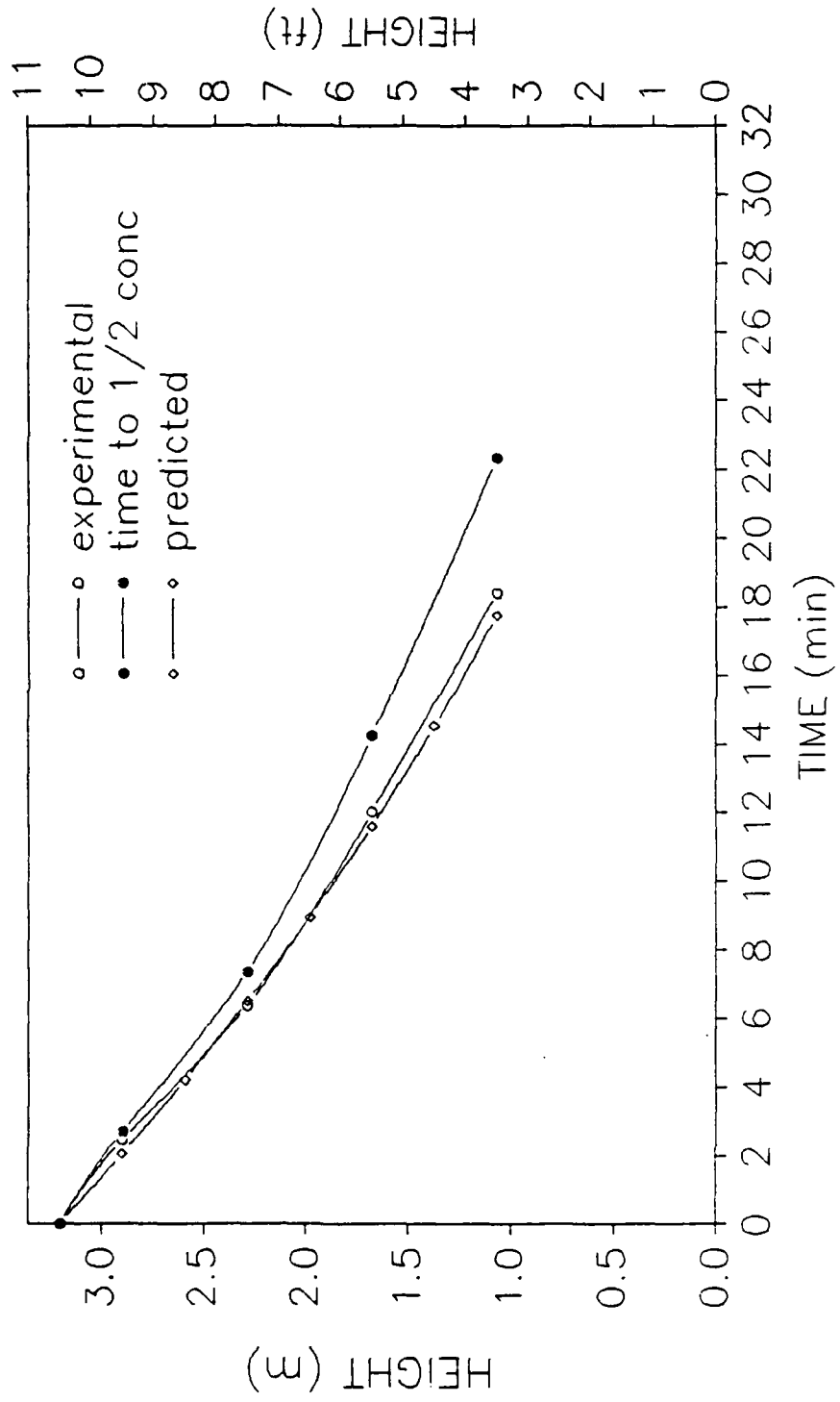
Fig. 10a – Interphase height comparison
for Halon 1301 – 15.24 cm (6 in) leak
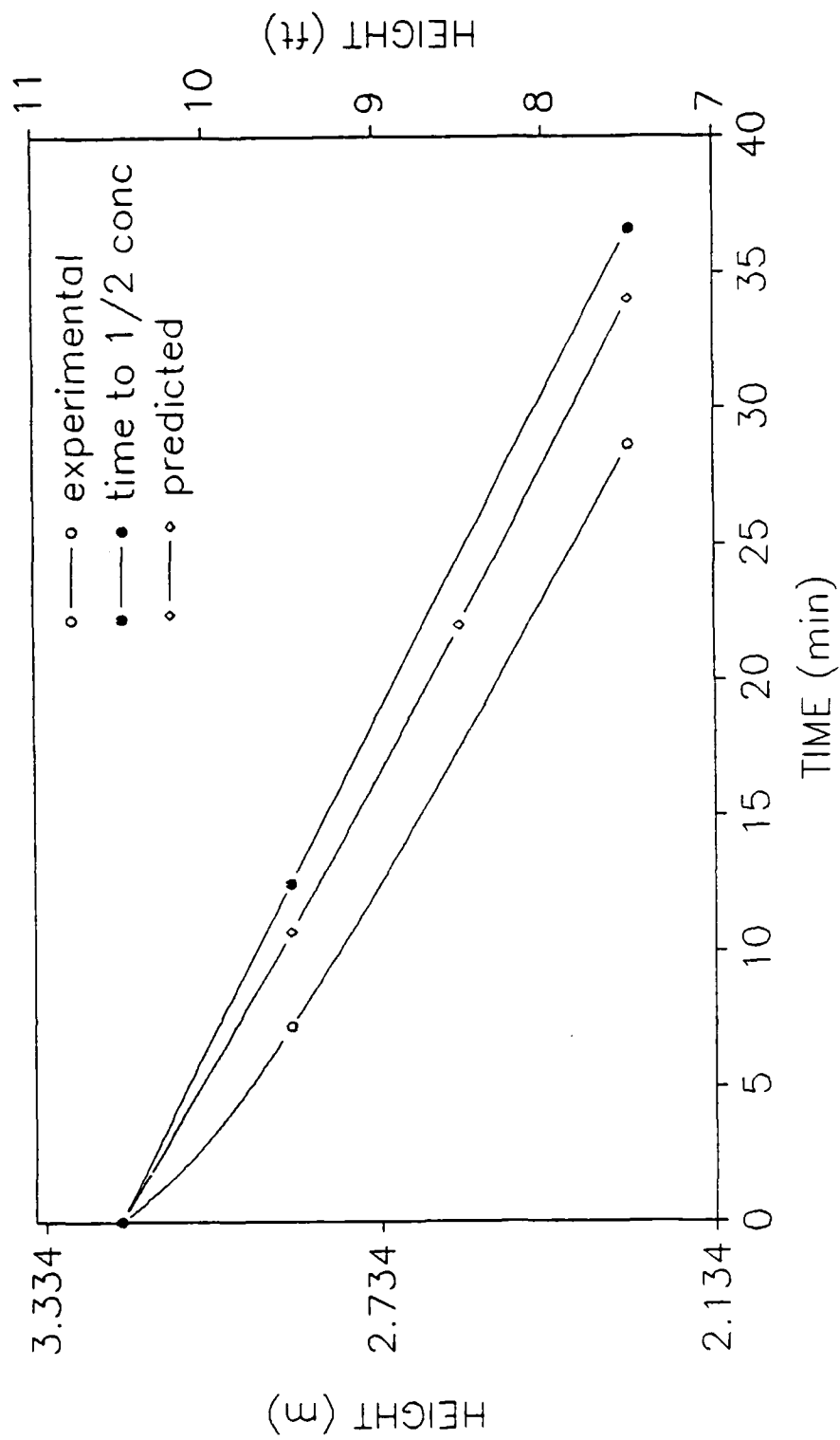
Fig. 10b – Interphase height comparison
for Halon 1301 – 6 cm (2.5 in) leak

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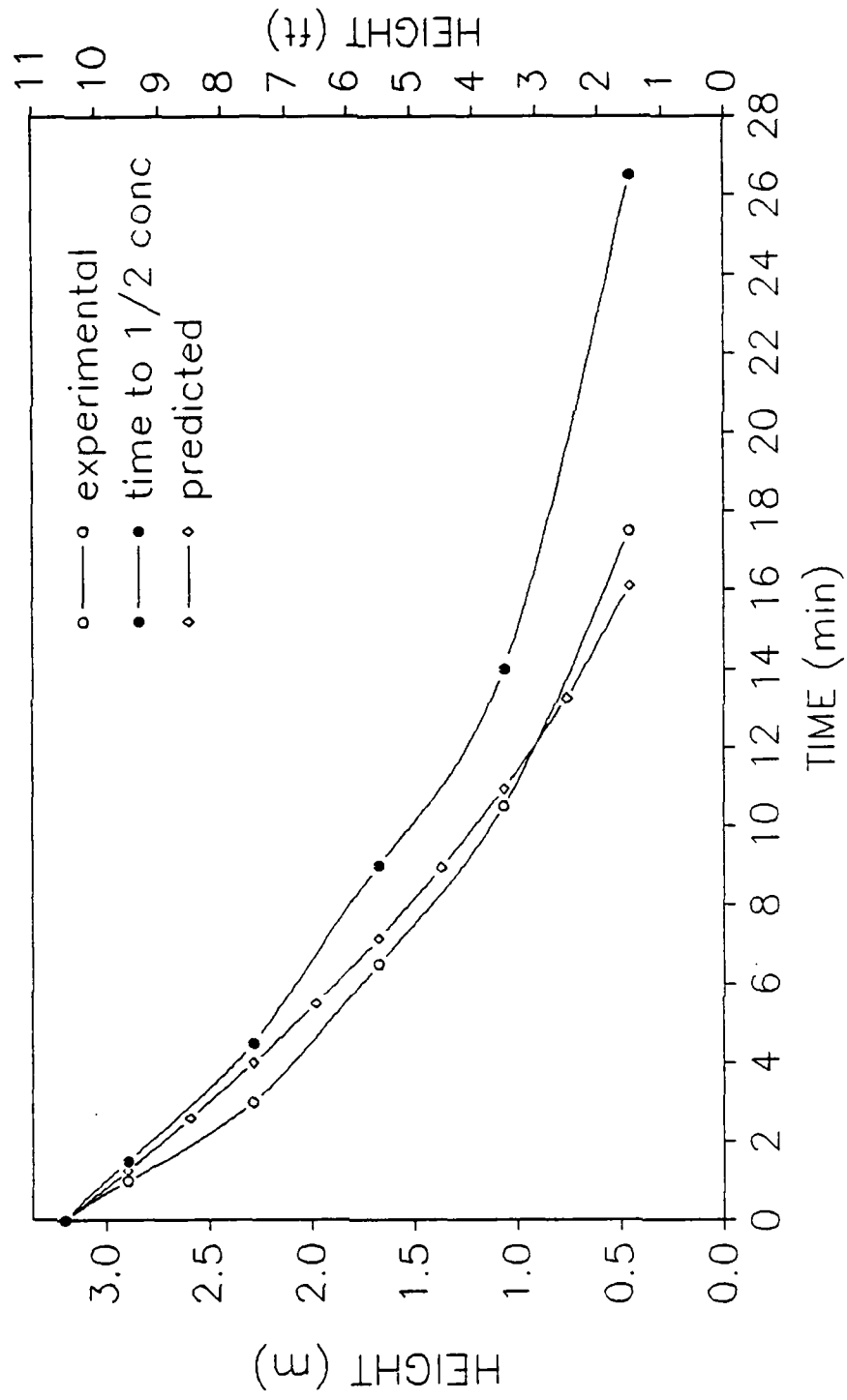
Fig. 11 – Interphase height comparison
for R-22 – 20.8 cm (8 in) leaks
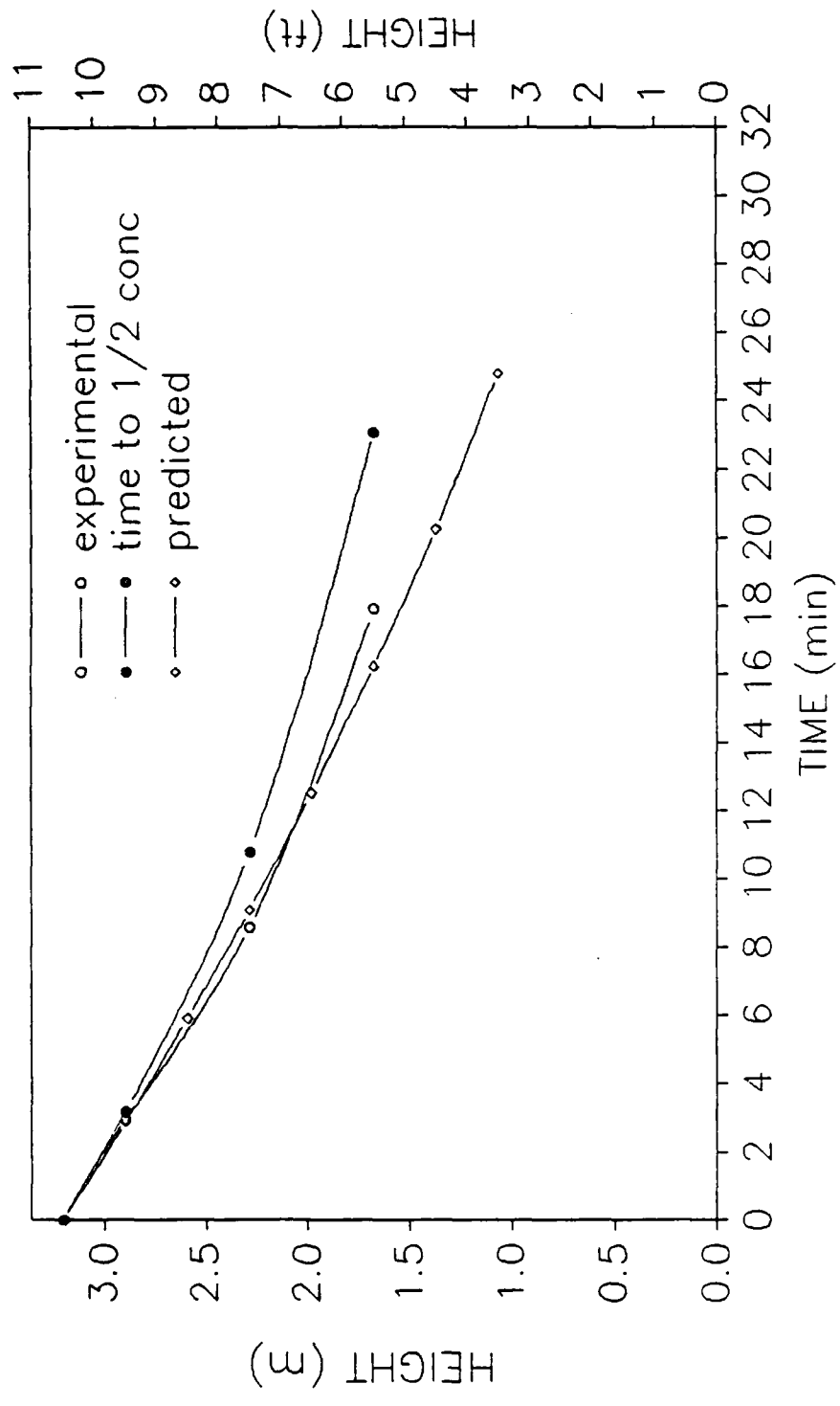
Fig. 11a — Interphase height comparison for R-22 — 15.24 cm (6 in) leaks
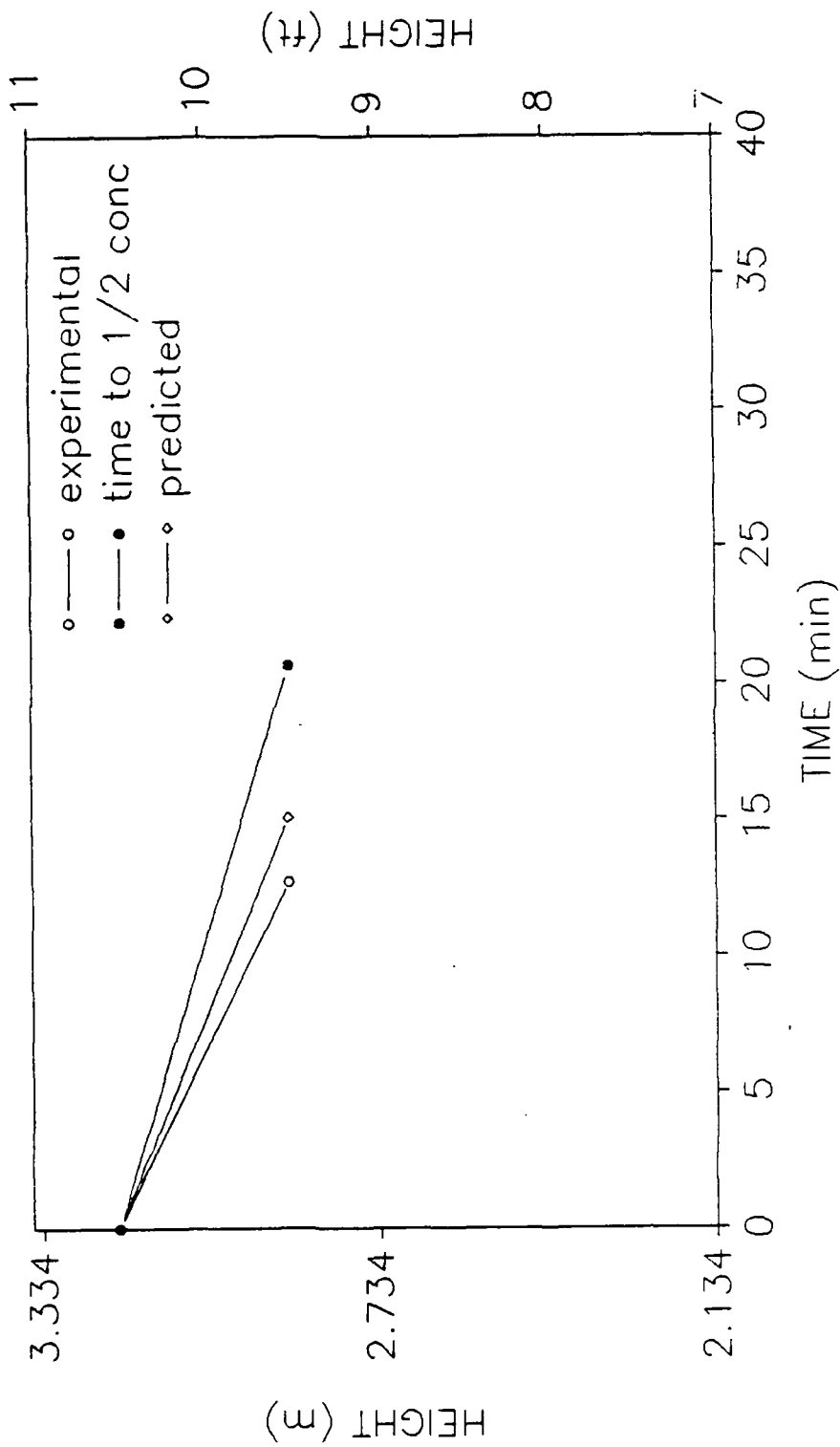
Fig. 11b – Interphase height comparison
for R–22 – 6 cm (2.5 in) leaks

legend:
—○— experimental
—●— time to 1/2 conc
—◇— predicted
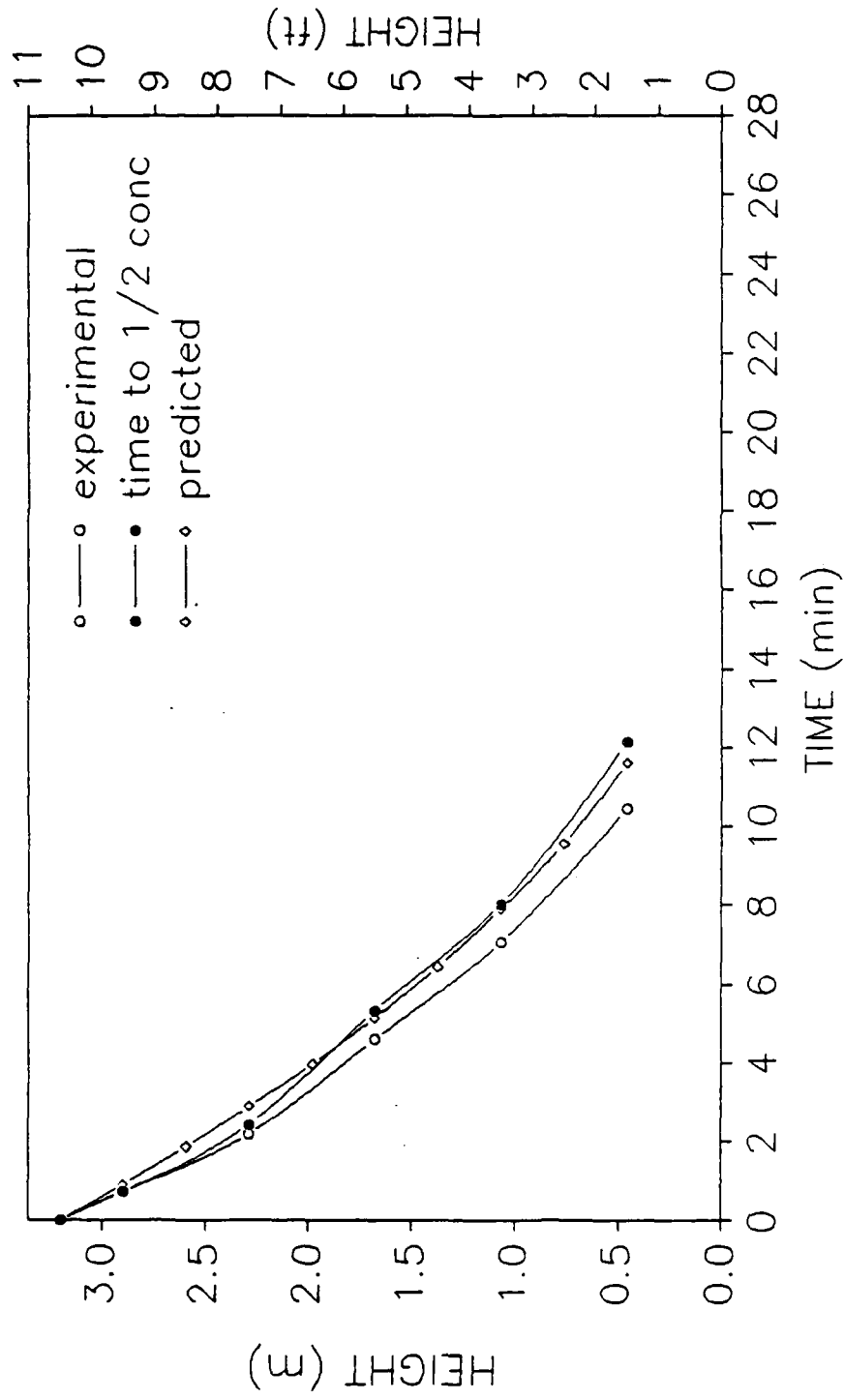
Fig. 12 – Interphase height comparison
for SF6 – 20.8 cm (8 in) leaks

experimental
time to 1/2 conc
predicted

TIME (min)
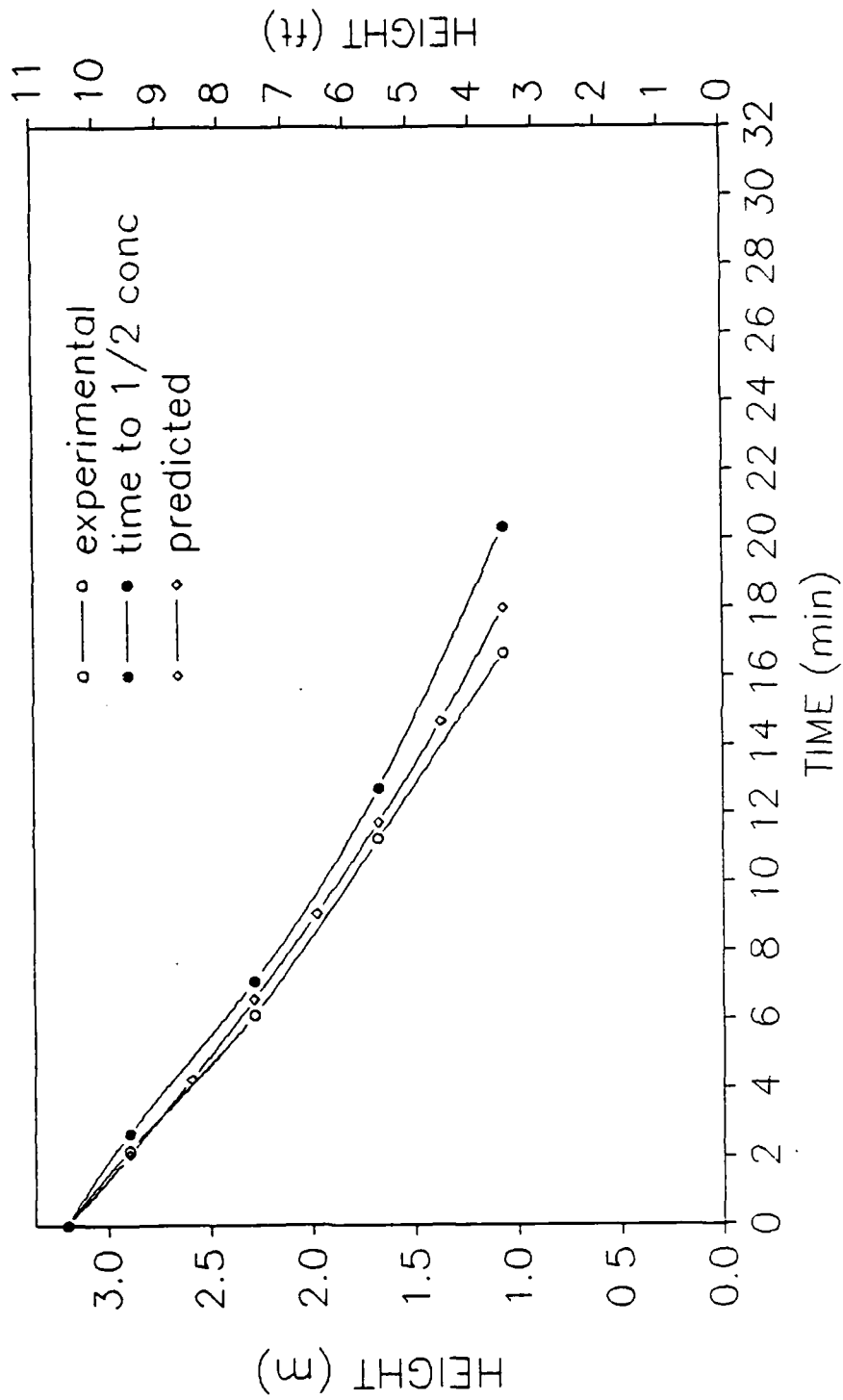
HEIGHT (ft)

HEIGHT (m)

Fig. 12a -- Interphase height comparison
for SF6 - 15.24 cm (6 in) leaks
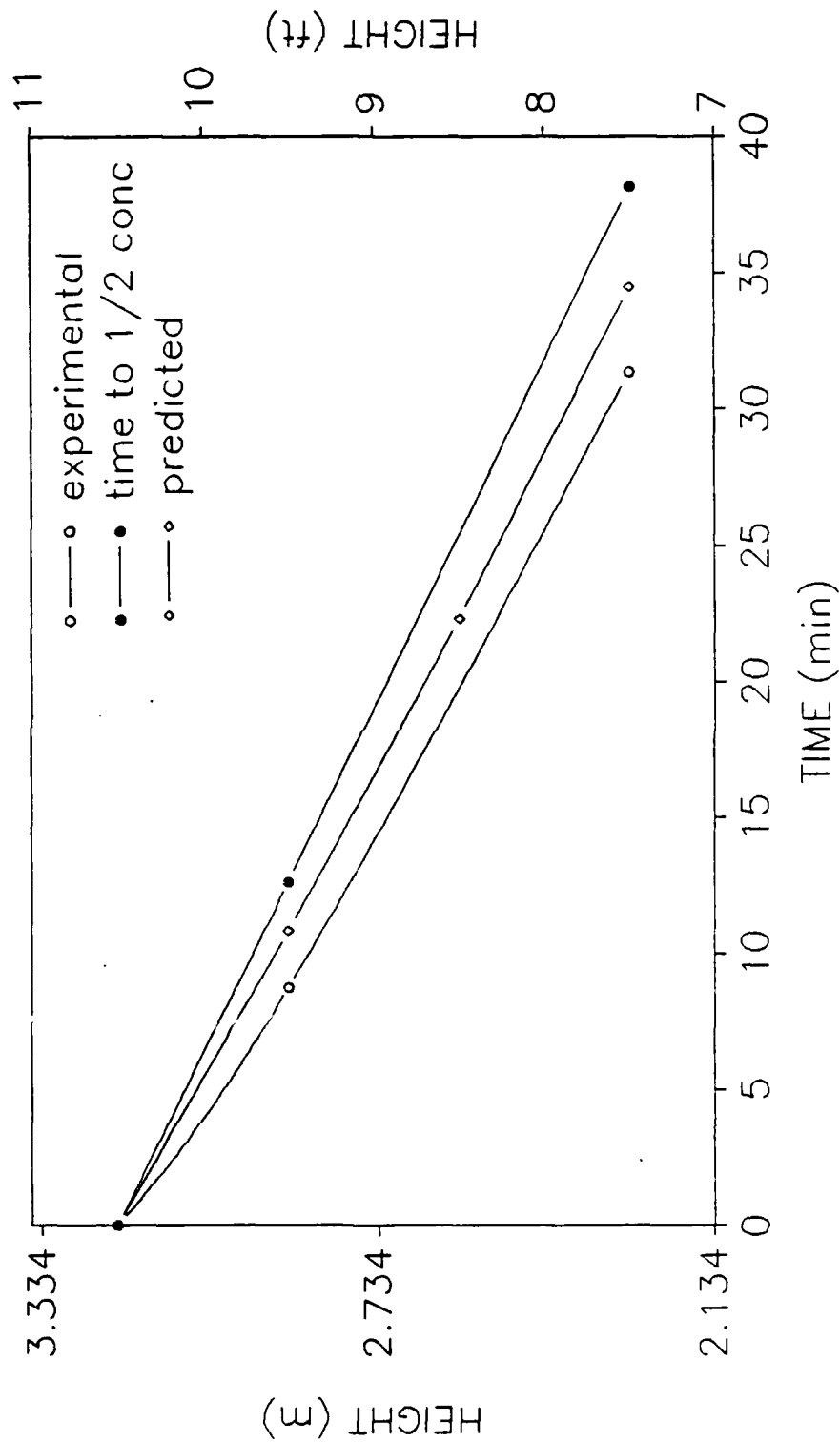
Fig. 12b – Interphase height comparison
for SF6 – 6 cm (2.5 in) leaks
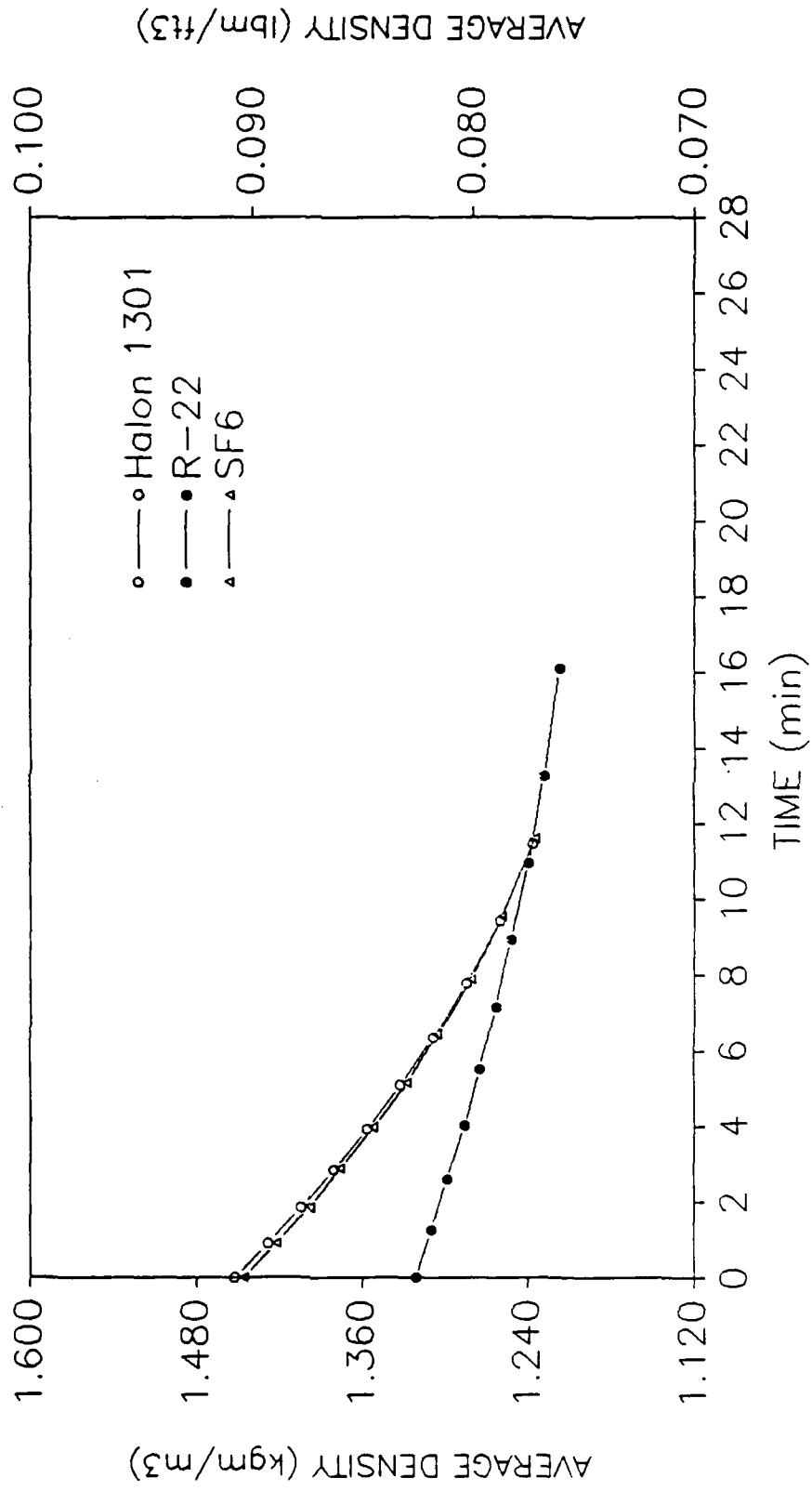
Fig. 13 — Predicted average density for 20.8 cm (8 in) leaks
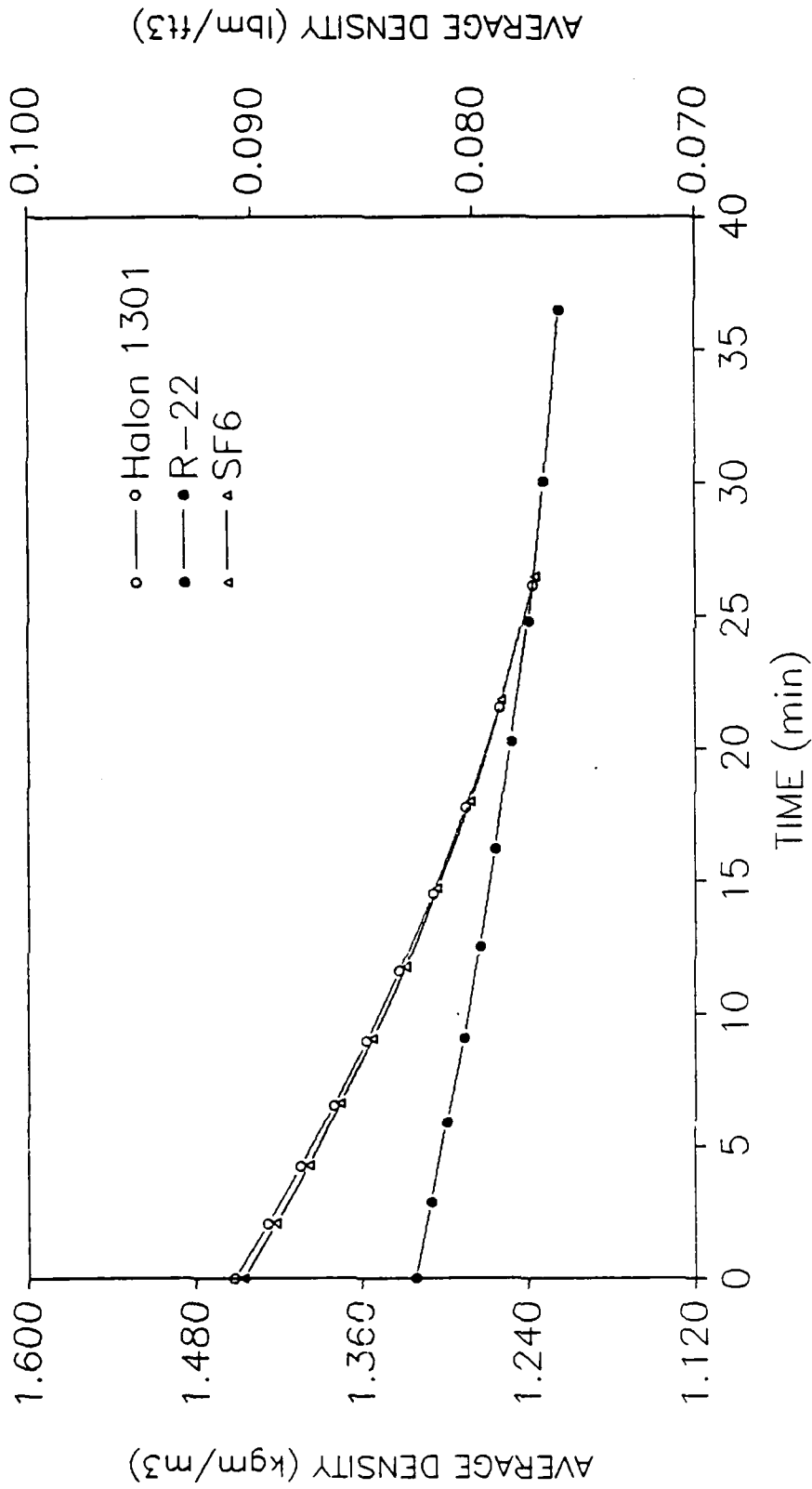
Fig. 13a – Predicted average density for 15.24 cm (6 in) leaks
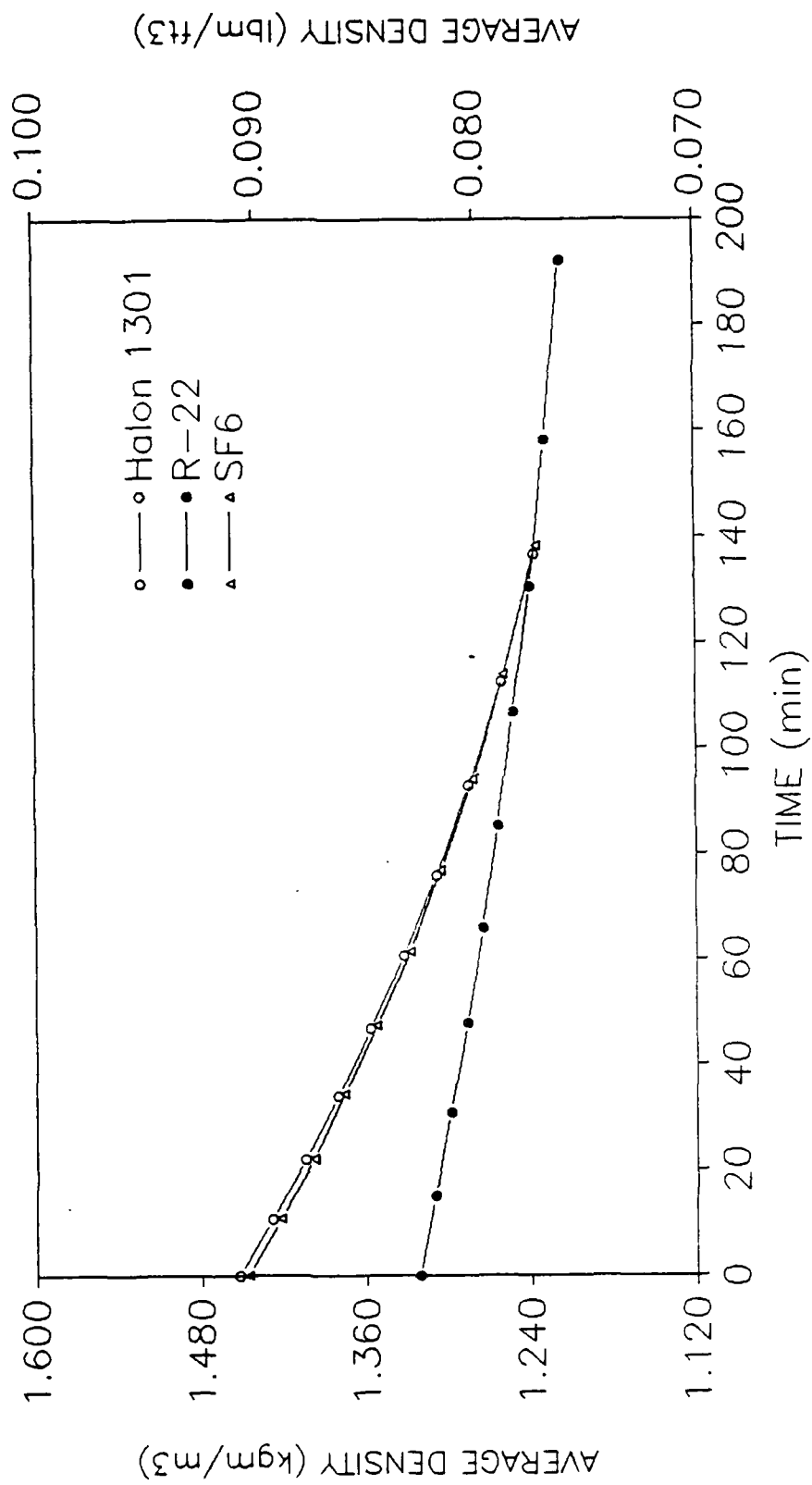
Fig. 13b – Predicted average density for 6 cm (2.5 in) leaks
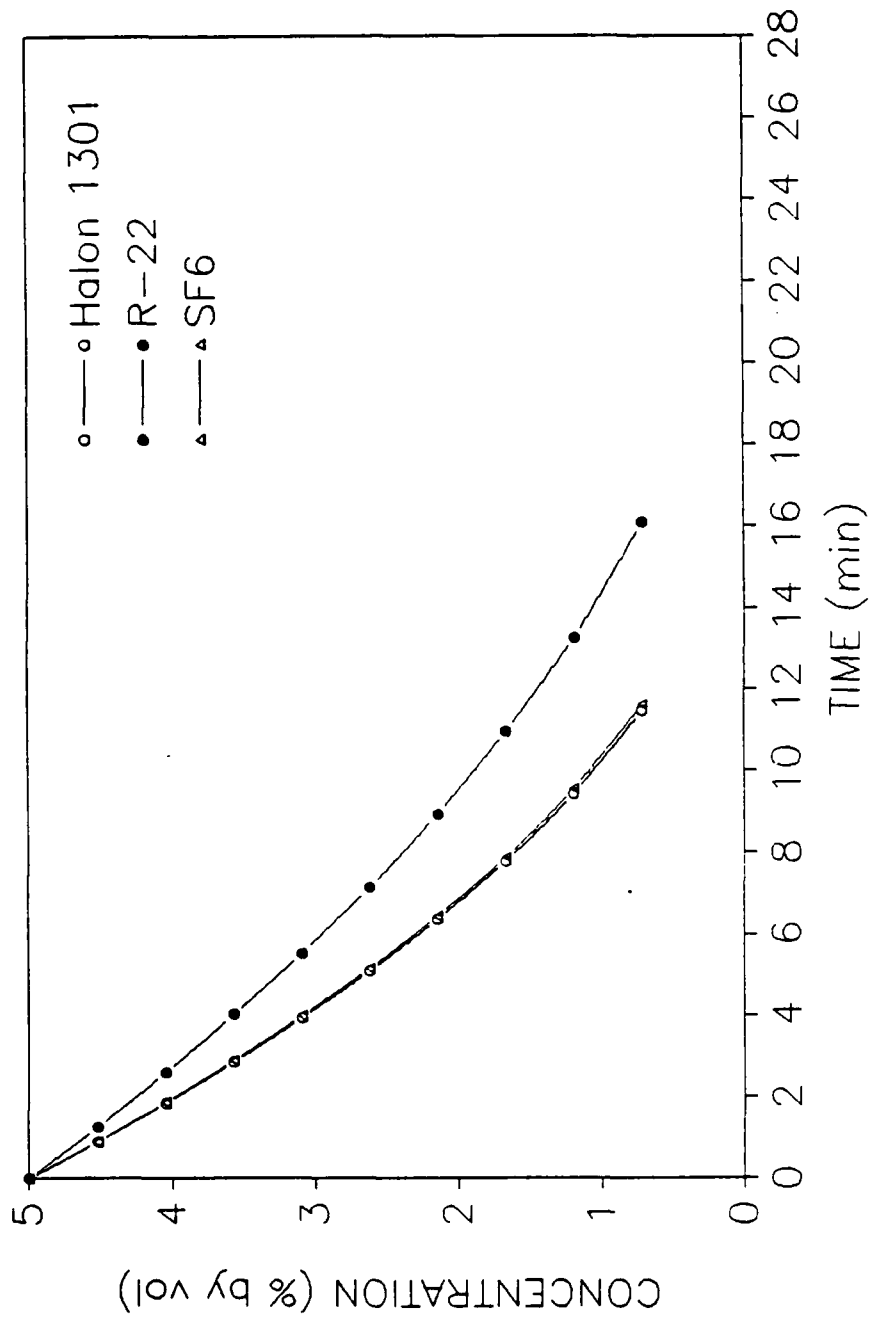
Fig. 14 – Predicted average concentration for 20.8 cm (8 in) leaks
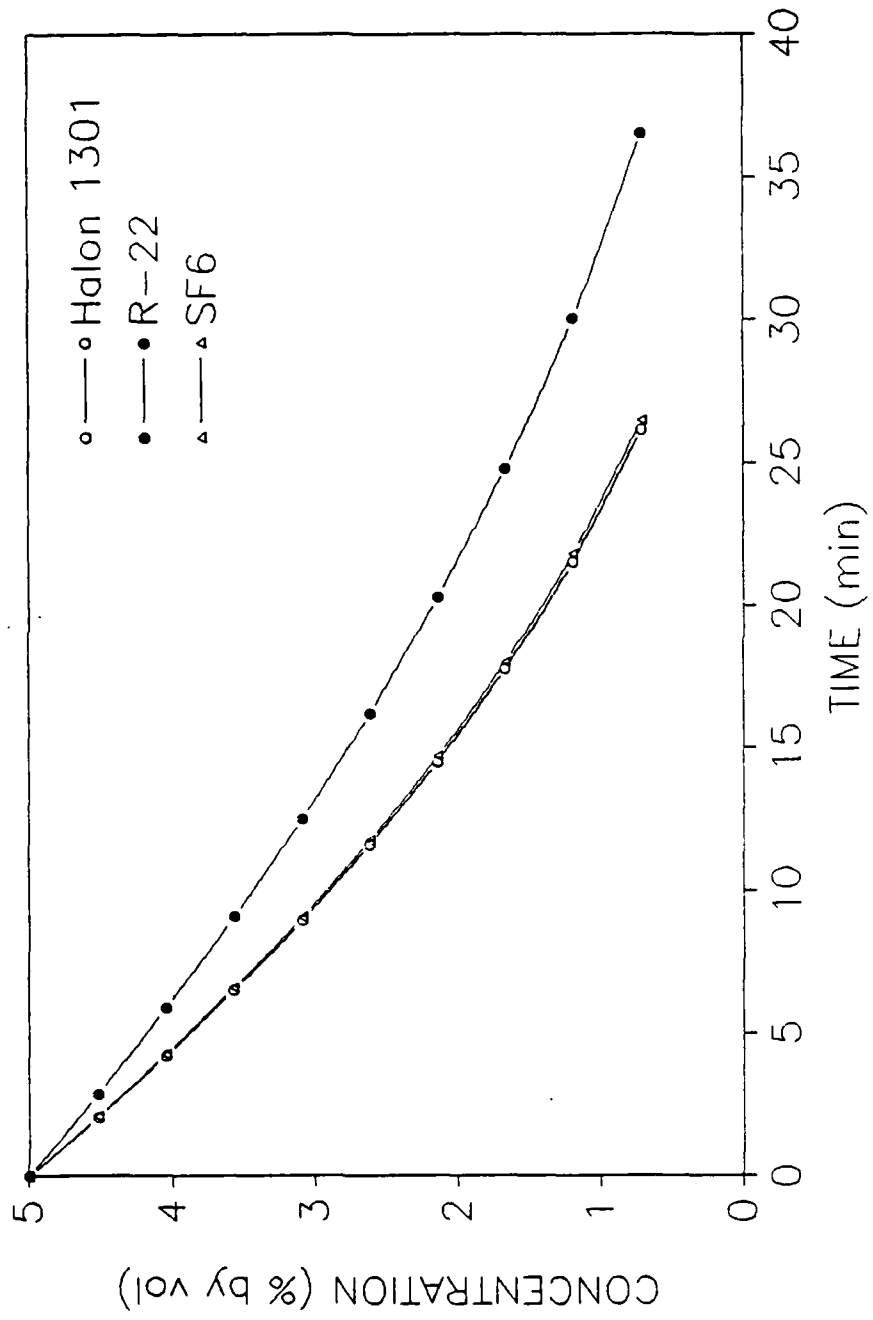
Fig. 14a — Predicted average concentration for 15.24 cm (6 in) leaks
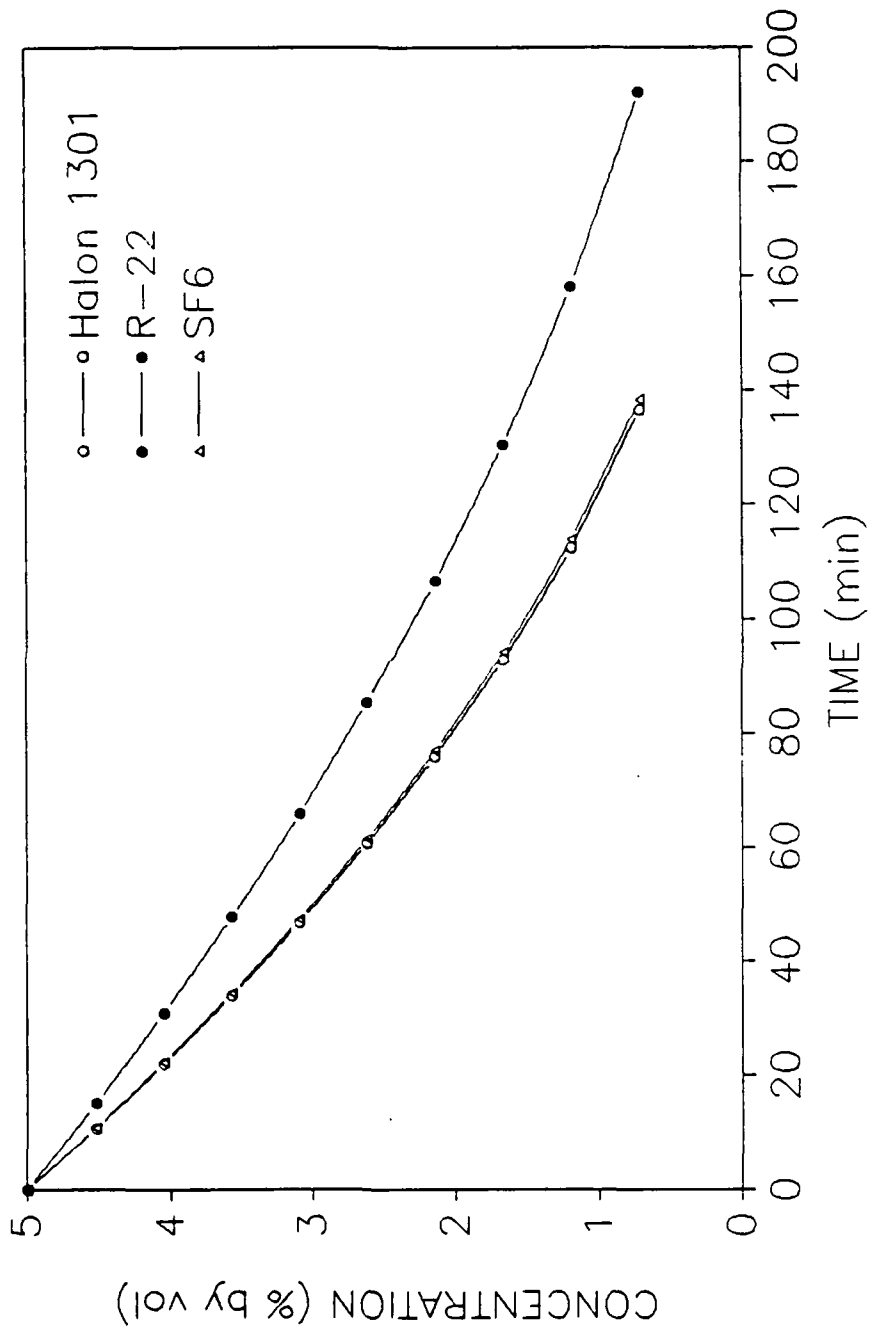
Fig. 14b – Predicted average concentration for 6 cm (2.5 in) leaks

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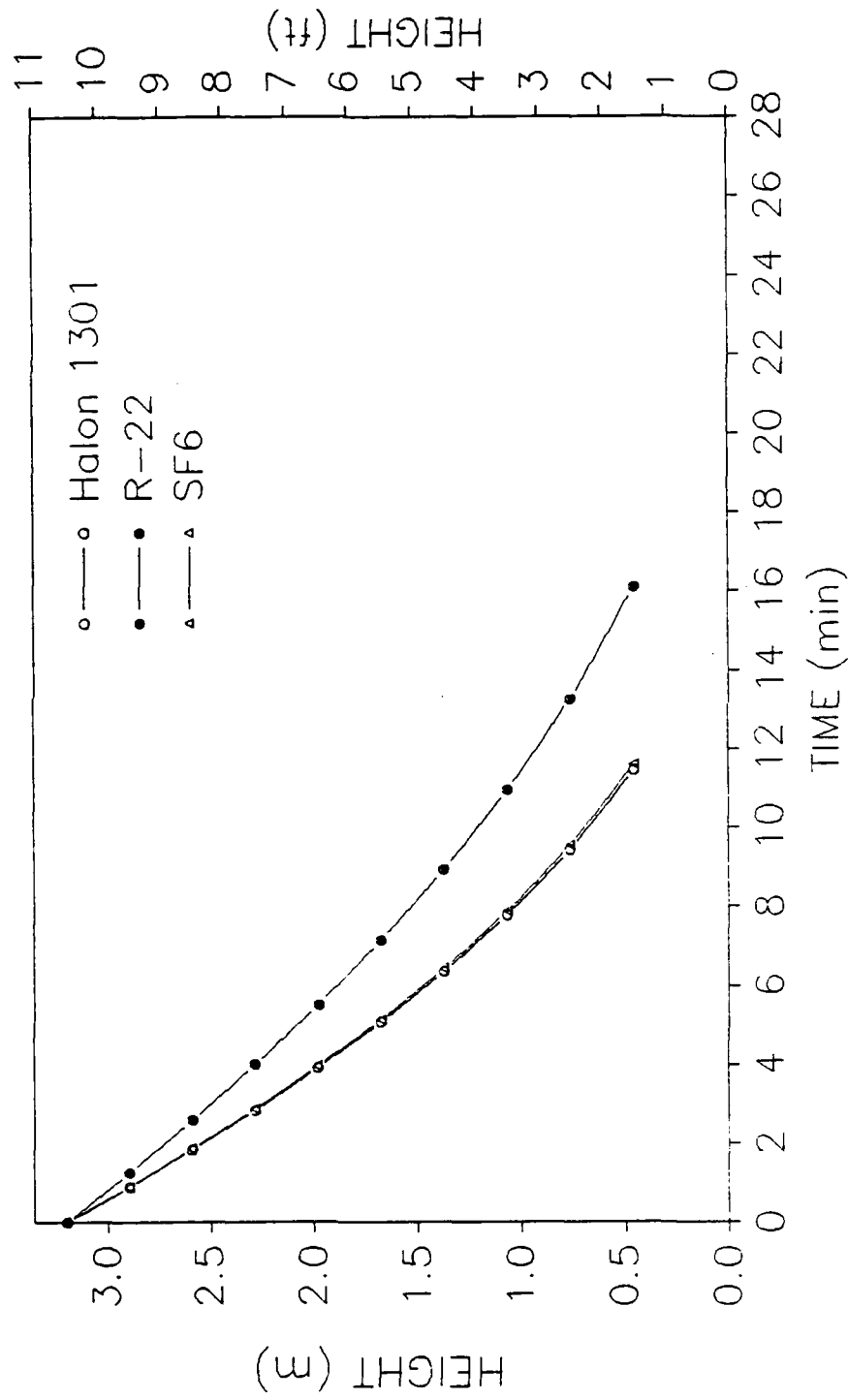
Fig. 15 – Predicted interphase height for 20.8 cm (8 in) leaks
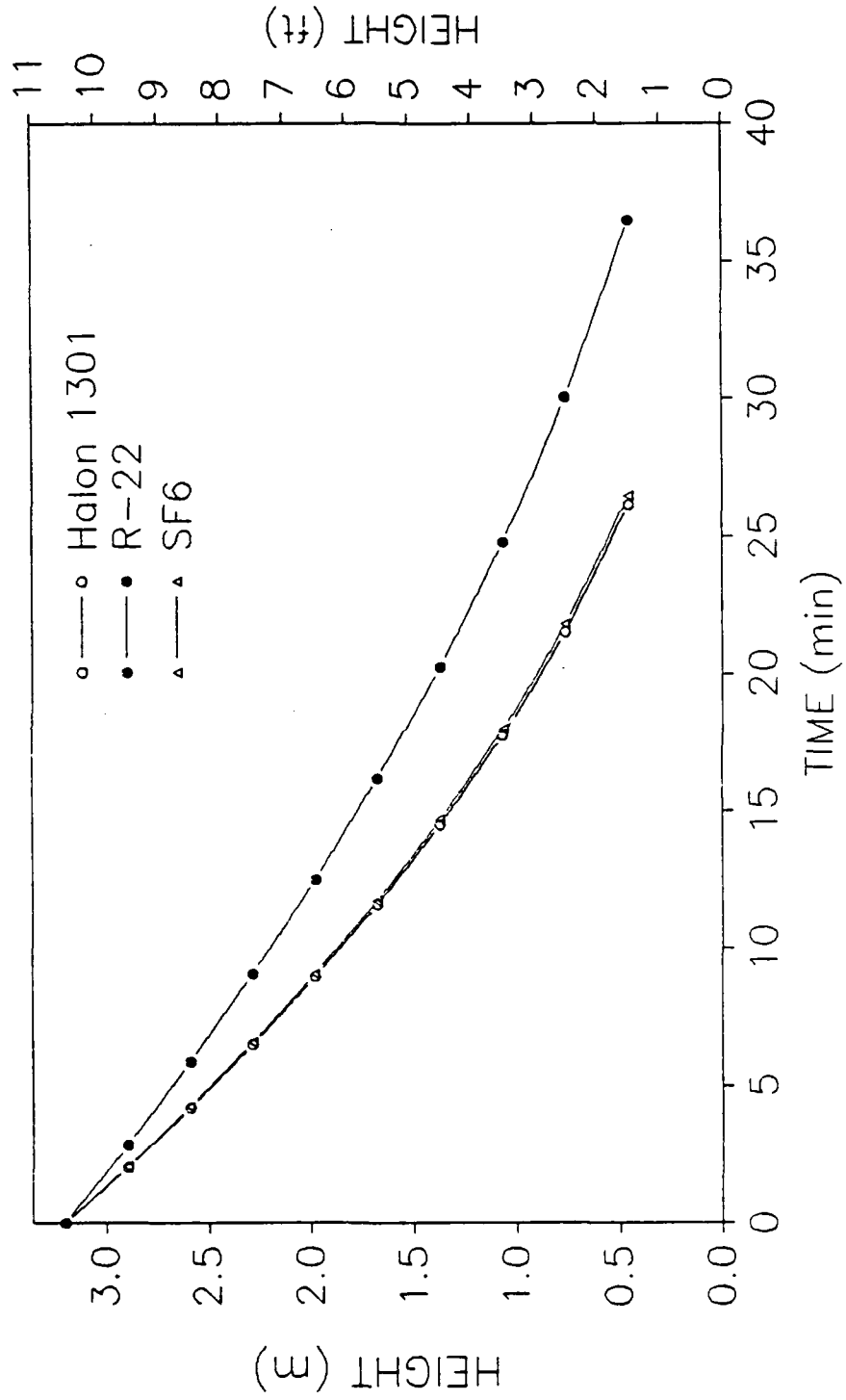
Fig. 15a – Predicted interphase height for 15.24 cm (6 in) leaks
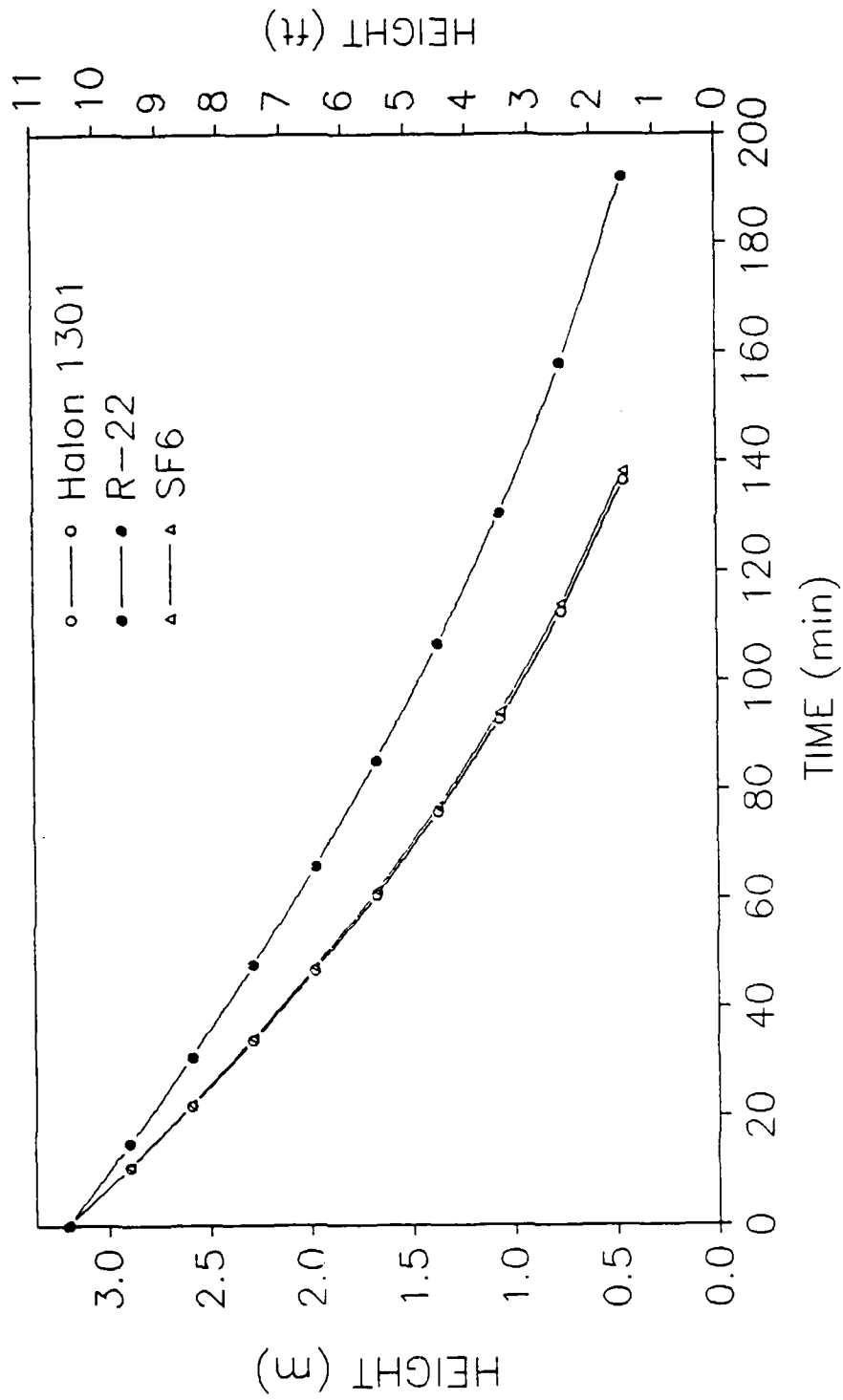
Fig. 15b – Predicted interphase height for 6 cm (2.5 in) leaks

Fig. 16 — Time to 1/2 concentration — average density for 20.8 cm (8 in) leaks

AVERAGE DENSITY (lbm/ft3)

AVERAGE DENSITY (kgm/m3)

TIME (min)

o Halon 1301
• R−22
▵ SF6
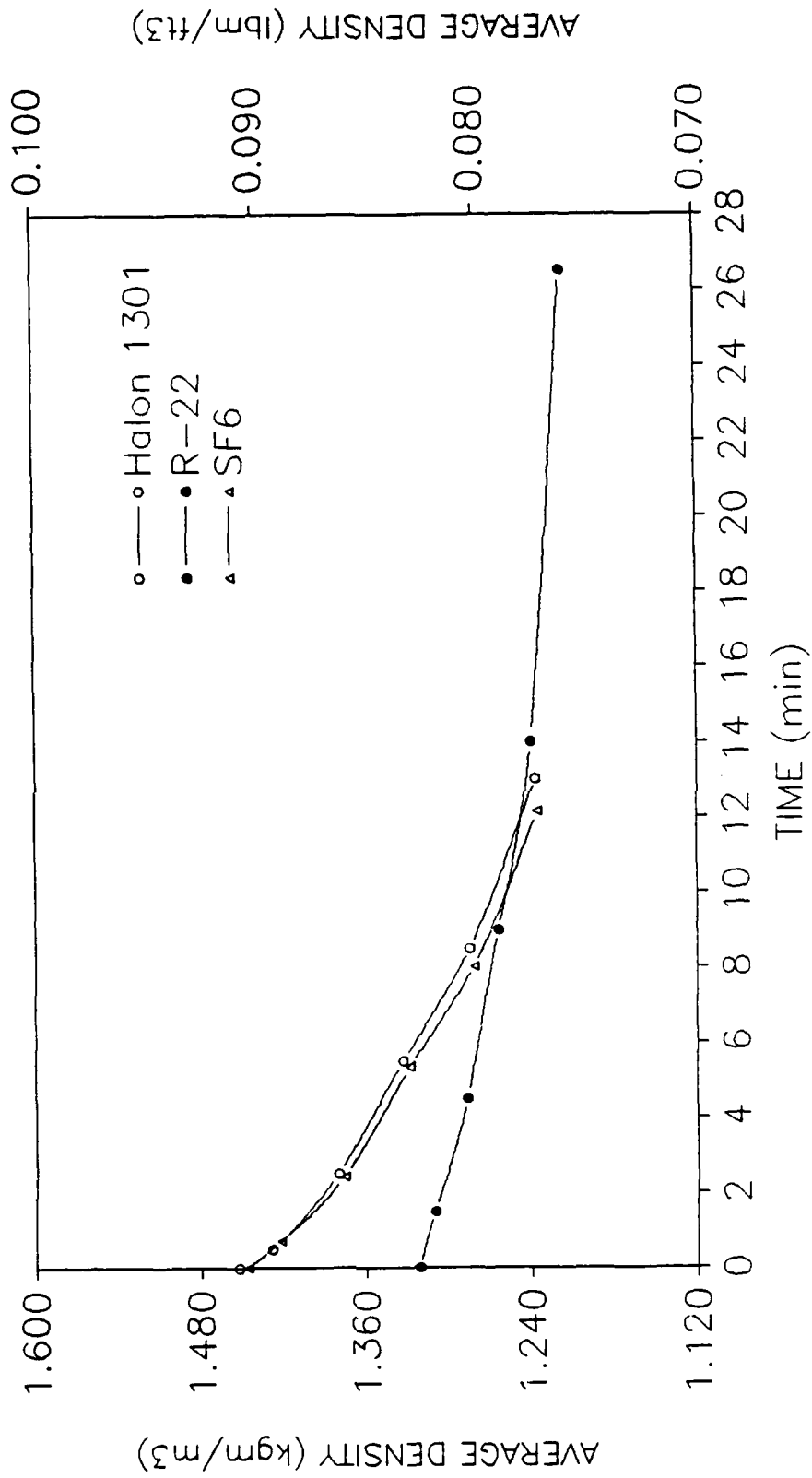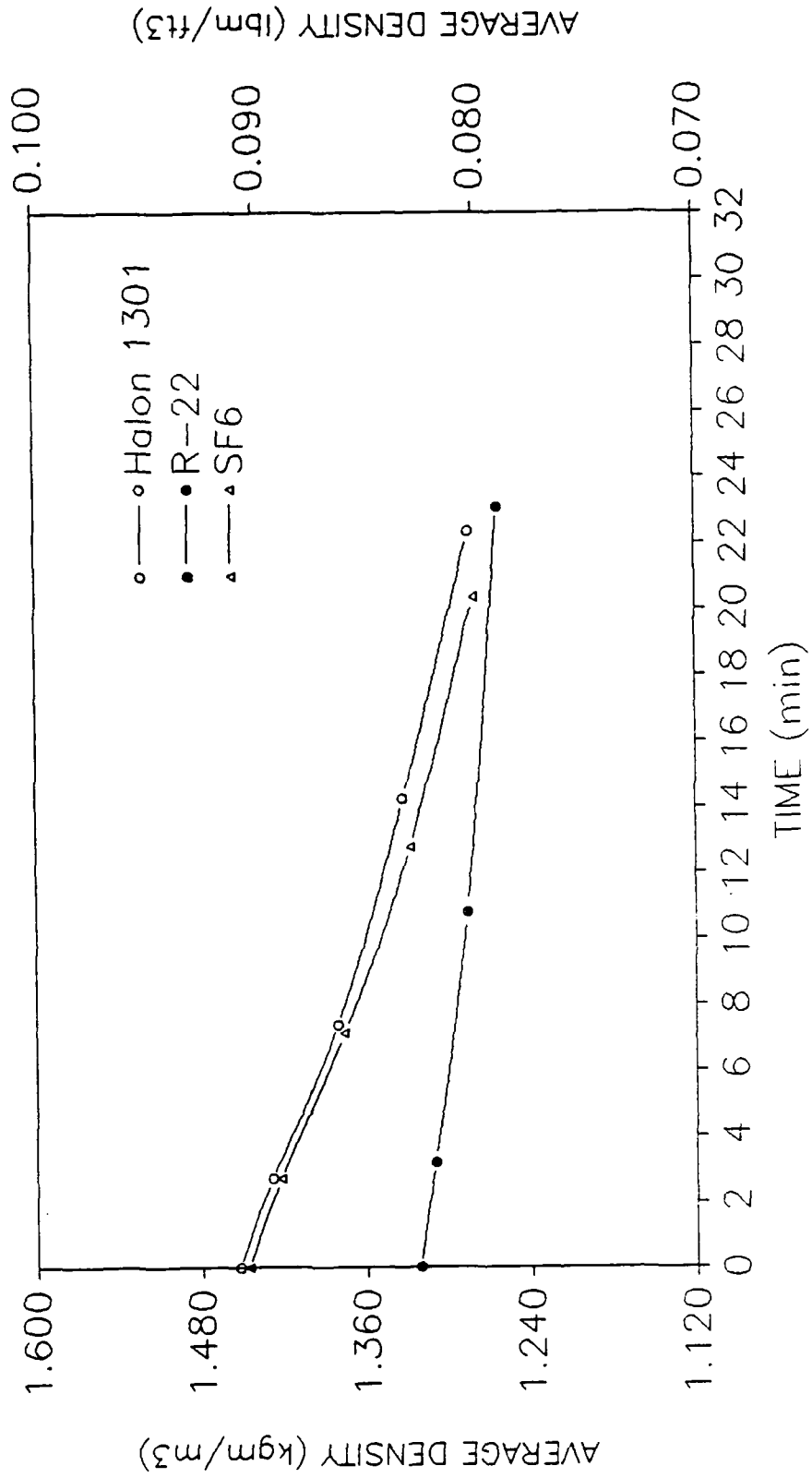
Fig. 16a – Time to 1/2 concentration – average density for 15.24 cm (6 in) leaks

65
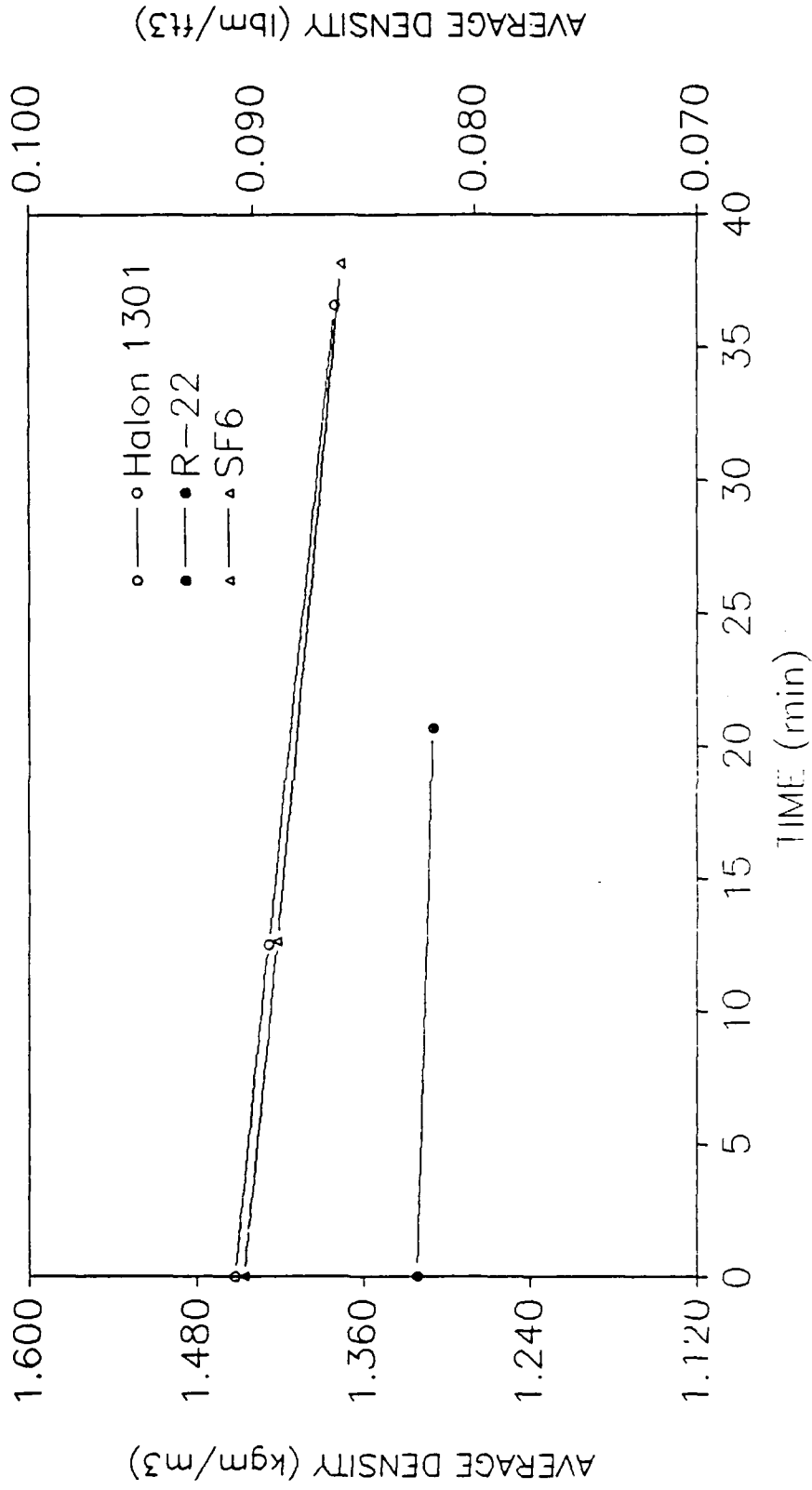
Fig. 16b – Time to 1/2 concentration – average density for 6 cm (2.5 in) leaks
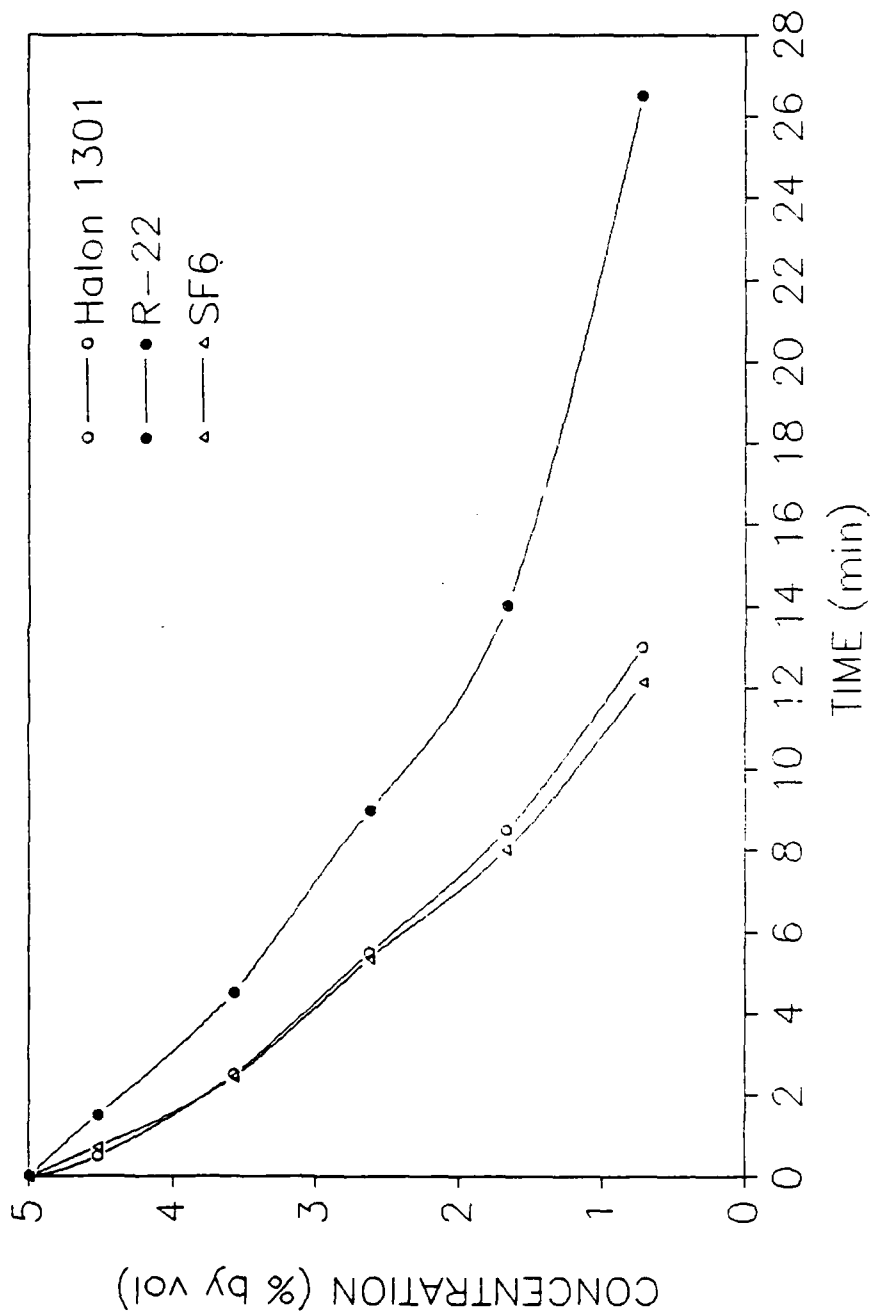
Fig. 17 – Time to 1/2 concentration – average concentration
for 20.80 cm (8 in) leak
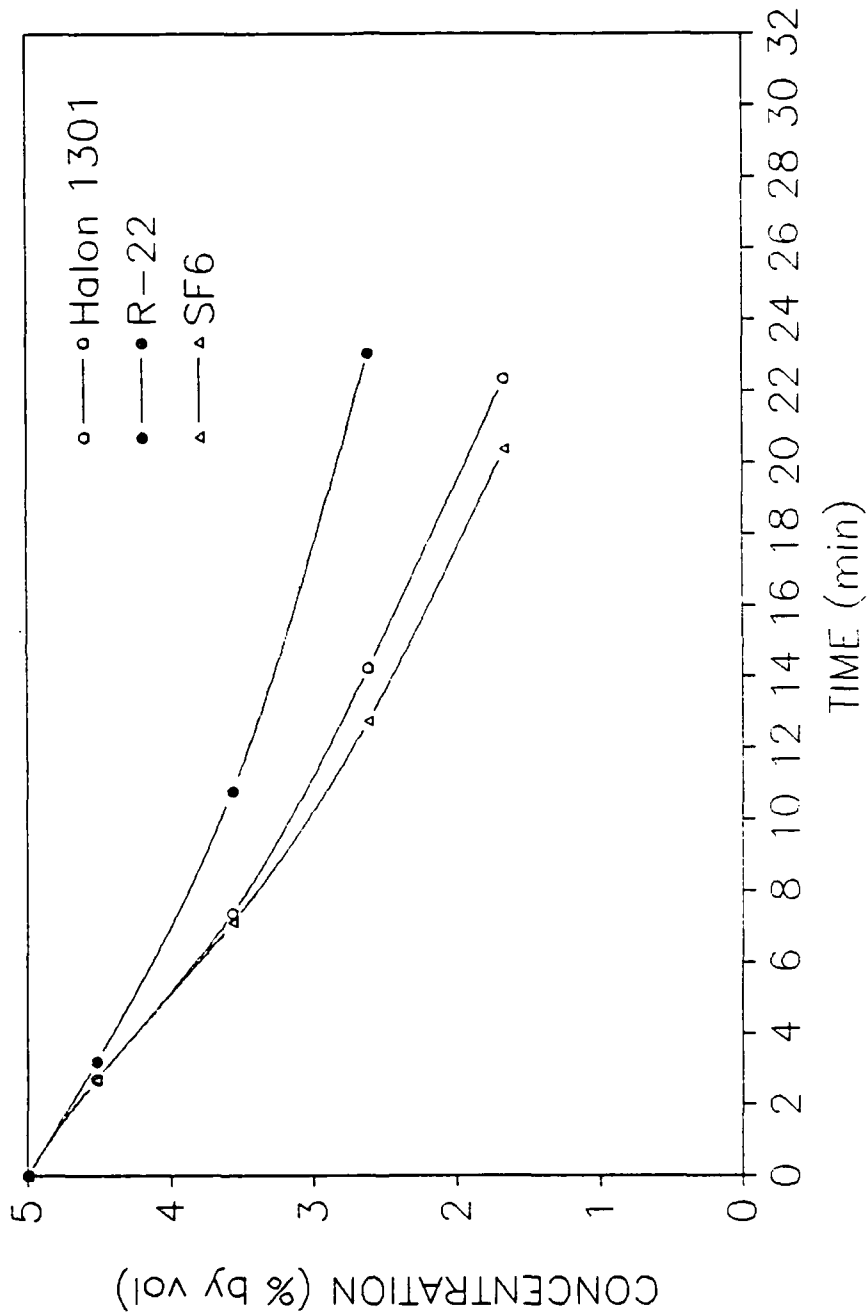
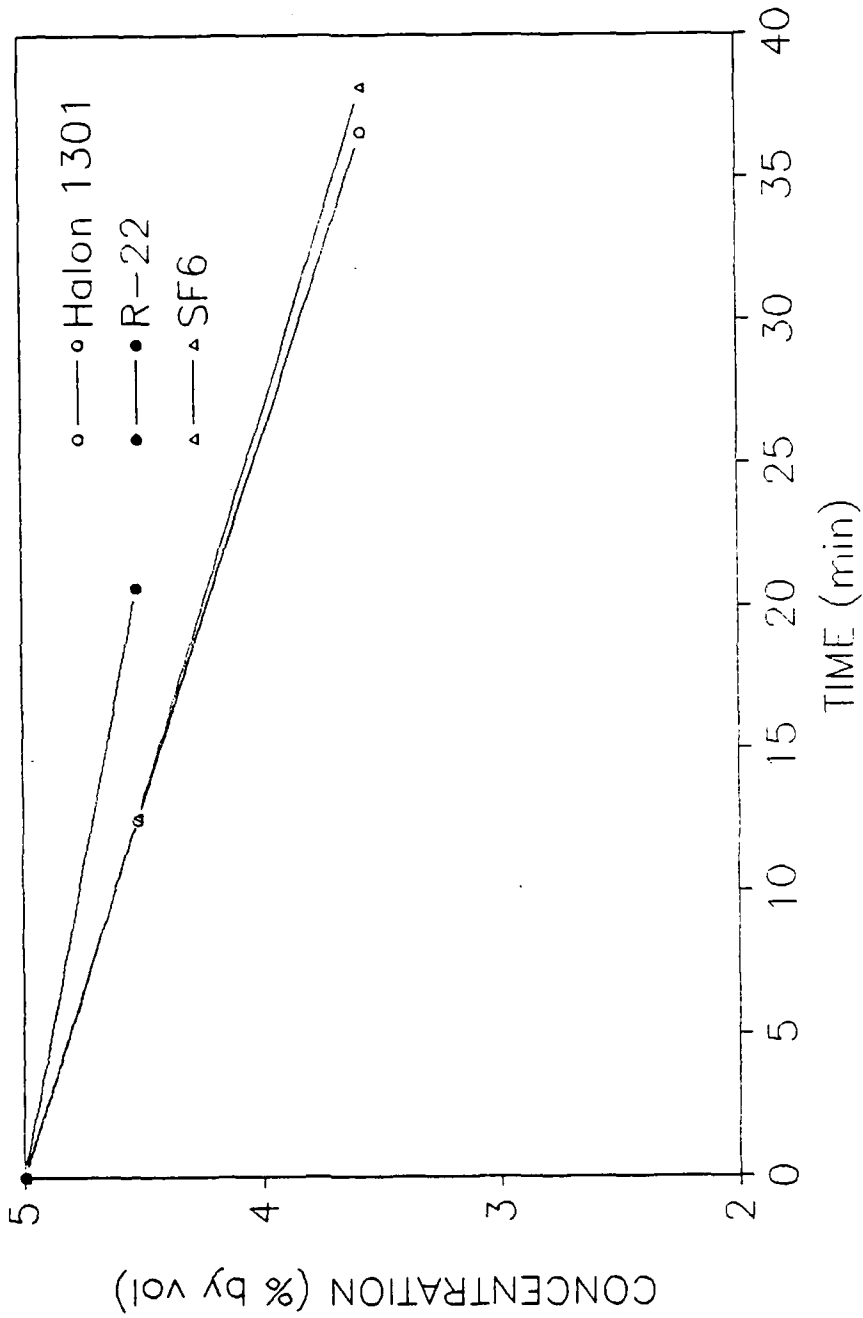Fig. 17a – Time to 1/2 concentration – average concentration
for 15.24 cm (6 in) leaks

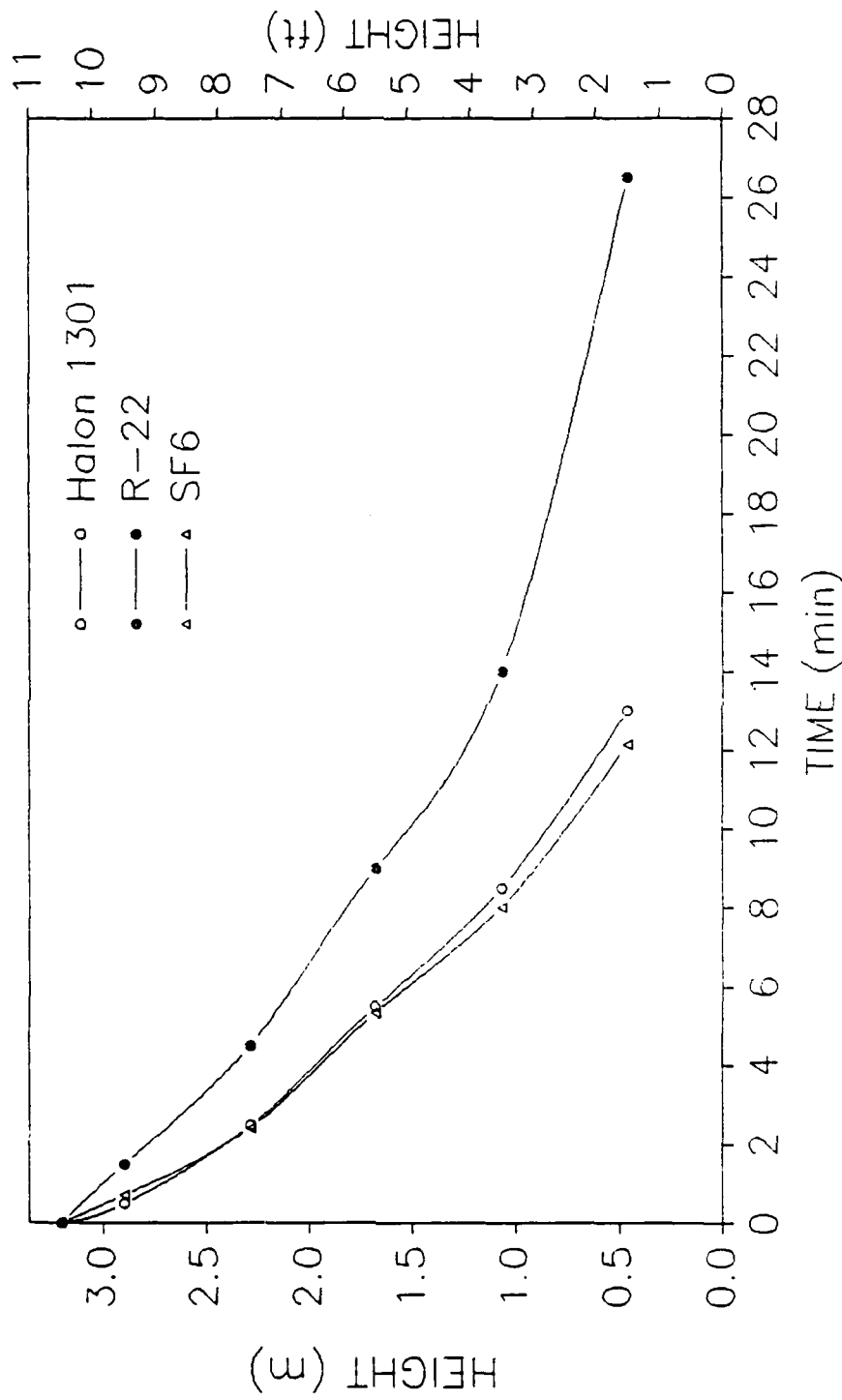Fig. 17b – Time to 1/2 concentration – average concentration for 6 cm (2.5 in) leaks

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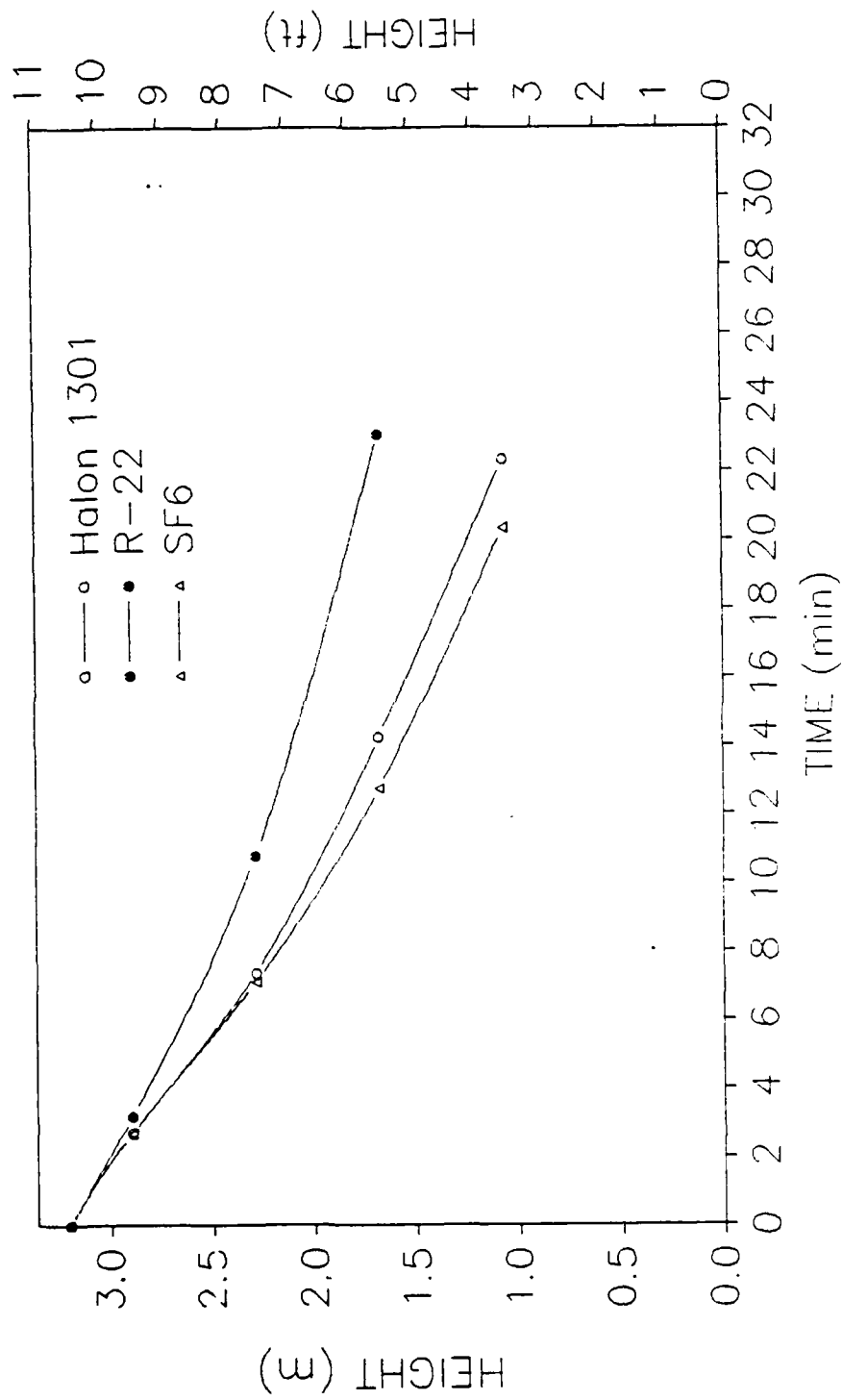Fig. 18 — Time to 1/2 concentration — interphase height for 20.8 cm (8 in) leaks

Fig. 18a — Time to 1/2 concentration -- interphase height
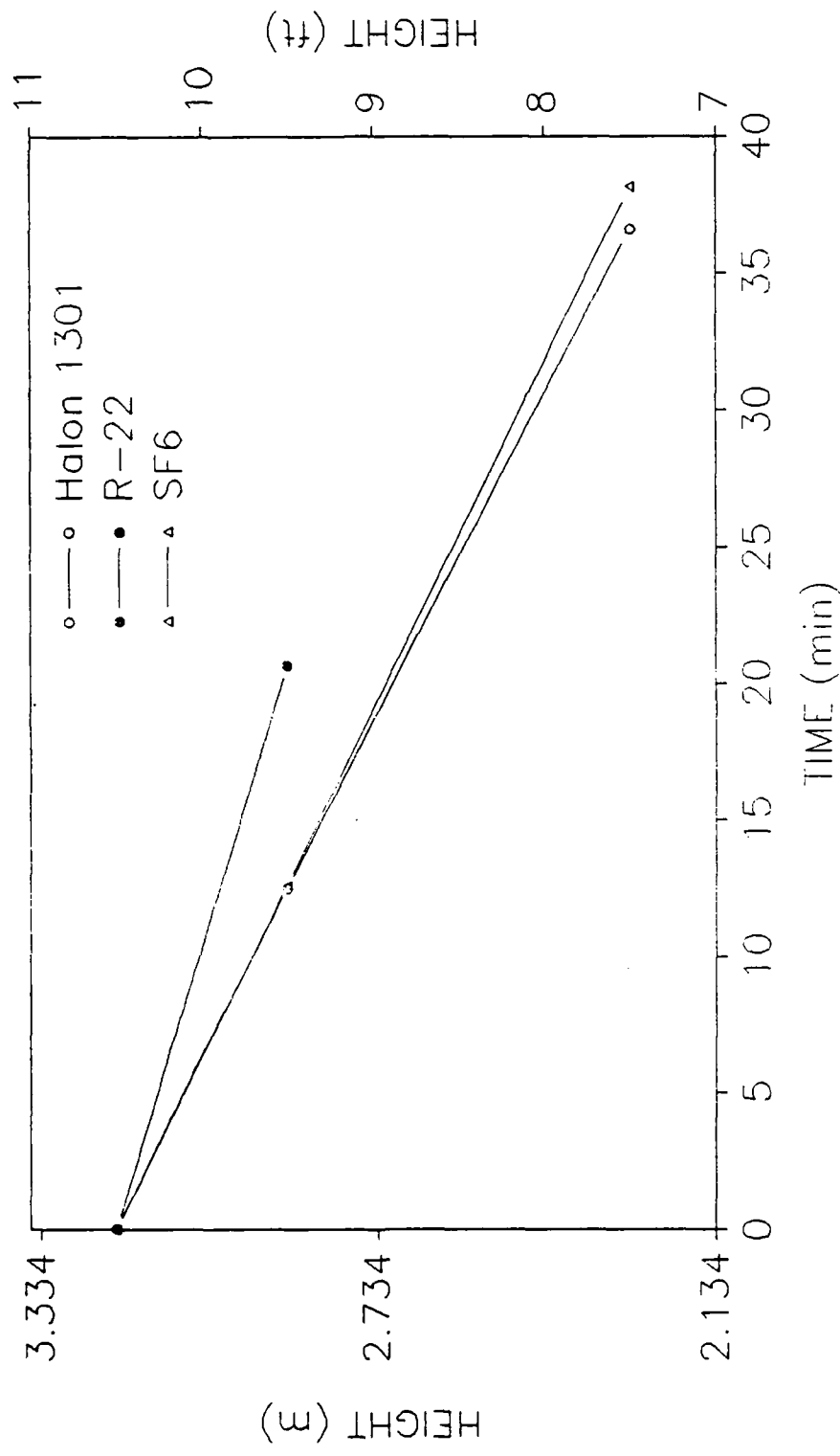for 15.24 cm (6 in) leaks

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Fig. 18b – Time to 1/2 concentration – interphase height
for 6 cm (2.5 in) leaks