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THE DESIGN AND MARKETING OF A NEW FAIL-SAFE DEVICE FOR
GAS APPLIANCES

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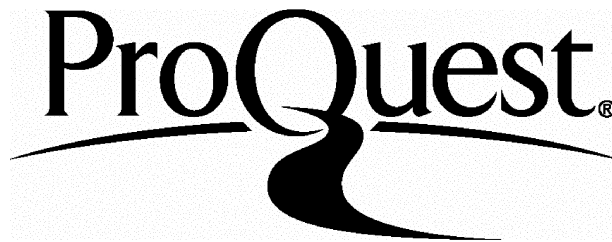
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ABSTRACT

The mercury flame failure device (F.F.D.) has now been in existence for approximately 30 years and in the United States, Canada and Britain there is now estimated to be a field population of 42,000,000 of these controls, with a current production rate of 2,350,000 units per year. Recently several problems have been identified which threaten the future of the mercury F.F.D., notably the toxicity of the mercury fill, and the relatively short life of the devices under some operating conditions.

This work examines the background to the mercury F.F.D. and the problems associated with it. A new type of F.F.D. was developed, for which patents have been applied. This device was filled with an inert gas, and was found to have all of the advantages of the mercury F.F.D., without the problems associated with the mercury. Prototypes were constructed which had sufficient performance and reliability to substitute for the mercury F.F.D..

Computer programs were developed to enable performance predictions to be made for gas filled devices and design data is given to enable the optimum design parameters to be selected for a particular application. The reliability problems associated with the new device were investigated and suggestions are made to enable maximum reliability to be achieved.

Finally the marketing of the new F.F.D. was studied. The existing market for the mercury F.F.D. was examined and the chances of the new F.F.D. succeeding in this market were considered. It was found that, given competant development, production and enthusiastic marketing, there were no reasons why the new F.F.D. should not succeed in the market place.

CHAPTER 1,

GENERAL HISTORY OF FLAME FAILURE DEVICES

1.1 Industrial Gas Appliances

The development of flame failure devices (F.F.D.'s) was pioneered in industrial gas appliances during the 1930's when the increasing use of thermostatic and other forms of automatic control on boilers and furnaces had resulted in increased chance of flame failure. Moore (1) lists several reasons for this, notably the rapid opening and closing of control valves causing pressure fluctuations in the gas supply, the effects of draughts on throttled back main burner flames, or pilot flames, the blockage of pilots by soot, dirt or corrosion, and finally the "uncouth" human element. The very fact that this new generation of appliances were automatic meant that they would be expected to function for long periods without manual supervision, so large volumes of gas could escape into the atmosphere before detection if a flame were to extinguish. This would result in an explosion hazard, and in the days of town gas a carbon monoxide poisoning hazard.

Consequently a flame failure detection system became a desirable part of a gas appliance control system, and with the cost of industrial appliances being quite high, the extra amount spent on flame failure detection could be easily justified. Thus before the last war many industrial gas installations were fitted with simple mechanical, electrical or electronic devices, many of which were imported from the U.S.A. (2). After 1945 a variety of British made F.F.D.'s began to appear on the market. Honeywell-Brown introduced a flame conductivity system in 1946, and were followed by Radiovisor Patent Ltd who produced a photo-electric detector, but both of these systems used vacuum tube electronics which made them expensive and unreliable. Several companies experimented with cheaper devices based

on the bimetallic principle (see section 2.2.), and in 1948
Perl Controls (3) introduced a British version of the thermo-
electric F.F.D. (see section 2.3) previously imported from
the U.S.A. Since then the thermoelectric device has found
widespread application in domestic and industrial appliances
due to its cheapness and reasonable reliability.

More recently the advent of cheap solid state electronic
components has made relatively low cost electronic F.F.D.'s
available, which because of their high speed of operation
are now widely used in industry. Table 1 lists a range of
flame sensing methods which could be used in an electronic
F.F.D. system.

In 1950 the Industrial Gas Development Committee published
a report (4) in which were laid down "indispensable character-
istics" and "desirable features" for F.F.D.'s as follows:-

(i) Indispensable Characteristics.
     Every flame failure device must:-
(a) Entirely prevent gas from being supplied to the
main burner until the pilot flame is established.
(b) If fitted correctly be free from an inherent
weakness in design which will give rise to failure to
danger.
(c) After flame failure, completely stop all gas flow
to the appliance, and require manual resetting.
(d) Be actuated only by a properly established pilot
flame sited to ignite the main burner without failure
or delay.
(e) Where it incorporates a gas - carrying component,
have an approved capacity within a permitted pressure
loss.

(ii) Desirable Characteristics.
      Every flame failure device should:-

(a) Be mechanically satisfactory and readily maintained.

(b) As far as practicable be protected against adjustment by unauthorised persons.

(c) Tolerate reasonable fluctuation in gas pressure, and combustion characteristics.

(d) Be reasonably unaffected by foreign matter.

(e) Tolerate reasonable variations in ambient temperature and air speed.

(f) Tolerate reasonable vibration and mechanical shock.

(g) Cut out when the pilot becomes too short or weak to ignite the gas at the main burner.

These guidelines formed the basis for future development of both F.F.D.'s themselves, and the regulations governing them.

1.2 Domestic Appliances

Generally speaking domestic appliances began to be fitted with F.F.D.'s at a later date than appliances in the less cost conscious industrial market. Here again it was the increasing use of automatic controls that had made this step necessary.

The first gas cookers (circa 1850) were very simple with only a gas tap to control oven temperature, but at the turn of the century the gas thermostat was developed in the U.S.A. This enabled the oven to operate automatically, as the thermostat controlled the temperature by modulating the main burner flame height. However when the flame was reduced by the thermostat there was an increased probability of flame failure, a dangerous situation which was at first circumvented by having a high "by-pass" setting on the thermostat, so that the flame was always sufficiently large to resist extinction. Unfortunately, "safe" by-pass rates meant that

low oven temperatures were difficult to control, and thus
some cooking operations were made difficult or impossible.

During the 1940's flame failure devices became available
on gas ranges made in the U.S.A. (5). At first these
were simple bimetallic devices, followed later by thermo-
electric devices, but neither of these systems were ideal
for cookers and proved to be troublesome. In 1958 the
Robertshaw Fulton Company in the U.S.A. developed the
mercury F.F.D. (see section 2.4) which for many years
has proved to be the best solution to the flame supervision
problem in gas cookers. This system proved to be more
reliable than the others, and it enabled cooker control
systems to be produced which could regulate oven temperatures
down as low as $60^{\circ}C$.

Mercury F.F.D.'s became available from British manufacturers
from 1965, and initially were only used in the control
systems on more expensive cookers in which safety was a
sales feature. From January 1 1972, British Gas document
WH/71/24 (6) made a F.F.D. a compulsory fitment on a gas
oven, if it were to obtain Gas Council approval. Most
manufacturers adopted the mercury F.F.D., but some
(Parkinson Cowan, Flavel and Main) used thermoelectric
F.F.D.'s in at least some of their production. The use
of thermoelectric F.F.D.'s on ovens has been made more
difficult since August 1976, when standing pilots on gas
cookers were banned by British Gas as a fuel saving measure.
This meant that thermoelectric F.F.D.'s had to be manually
reset (see section 2.3) at the start of each cooking cycle,
and the inconvenience of this to the consumer has prompted
some manufacturers to change from thermoelectric F.F.D.'s
to mercury F.F.D.'s.

At the time of nationalization of the gas industry,
(May 1 1949) gas had penetrated 11 million homes in
Britain, almost entirely due to gas cookers and water

heaters (7). Since then there has been a dramatic
increase in the variety of gas appliances used in the
British home. Gas heating has been responsible for much
of this. Central heating boilers and air heaters are now
found in many homes, and these must be fitted with a F.F.D.,
most of which are the thermoelectric type, although some
have been fitted with bimetallic F.F.D.'s. Radiant gas
fires are not at present fitted with F.F.D.'s as they are
manually controlled, but automatic wall mounted balanced
flue convector heaters are fitted with F.F.D.'s, generally
of the thermoelectric type.

Water heaters are still widely used in the U.K. These can
be of the multipoint type, single point type (geysers)
or the storage type. In this field the bimetallic strip
F.F.D. has been the most commonly used type, although
more recently thermoelectric devices have become popular.

Other appliances include refrigerators, not fitted with
F.F.D.s (except those using L.P.G.) due to their low gas
consumption, drying cabinets, which have been fitted with
all types of F.F.D., and greenhouse heaters which have
used mercury and thermoelectric F.F.D.s.

CHAPTER 2

SURVEY OF KNOWN METHODS OF FLAME DETECTION

2.1 Flame Detection Methods

Methods which need an electricity supply to operate them
are listed in table 1. They all need a solenoid valve to
control the gas flow, and most (except the mercury switch,
thermocouple switch, symmetrical diode ultra violet detectors
and the salt cell) require an amplifier to give enough
power to control the solenoid valve. Although some of
these methods have many attractions, their expence has
limited them to industrial gas appliances.

Table 2 reviews known methods of flame detection which
produce mechanical movement. The porous plug and Curie
Temperature devices have only been produced experimentally
at the American Gas Association Laboratories by Zielinski
(8) and have many problems associated with them. The
mercury, thermoelectric and bimetallic devices have all
seen extensive use, and their advantages and disadvantages
are well known. Their main advantages are that they are
cheap to make, reasonably reliable, and are totally self
contained, not needing any external power supply. These
features have ensured that most domestic appliance F.F.D
systems are of one of these types. They are examined in
detail in the following sections.

2.2 The bimetallic and unimetallic F.F.D.

In its most basic form this consists of a bimetallic
strip which when heated by a pilot flame, bends, and opens
a gas valve via some form of mechanical linkage. If the
flame should fail the bimetallic strip cools and gradually
shuts the valve.

Unfortunately there are a number of serious problems with

bimetallic devices. Prolonged use can cause the bimetallic element to warp (1) and hold the gas valve permanently open, and because the actuating mechanism is exposed it is easily tampered with.

An important problem from the appliance manufacturers point of view is that because of the mechanical linkage between the flame sensor and the gas valve, the F.F.D. has to be specially engineered for each application (or vice versa). Both the mercury and thermoelectric devices have a flexible connection between the flame sensor and the valve, which means that a standard device can be sold, which can then be bent to fit all burner configurations.

Many attempts have been made to improve this basic system. One idea was to use a rod surrounded by a tube of different material. The rod and tube which are fixed together at one end expand differentially when heated, and the difference in movement between rod and tube can be used to operate a valve. This system is more rugged that the bimetallic strip version, and is tamper proof. However the movements so far obtainable over a normal operating temperature range are minute unless a very long length is heated, so in general this device can only be used to control a low gas flow. Hence this type of F.F.D. has to be used in conjunction with a gas relay valve. This system was the basis of the Potterton rod type cut out device (1).

Bimetallic discs have been used in some systems such as that produced by De La Rue Gas Developments just after the war (1). Here a pilot flame played on a bimetallic disc and the movement of the disc centre operated a small valve via a system of levers. Again this valve could only control a low gas flow, and a gas relay had to be used in combination with it.

Unimetallic systems have also been developed (2, 9) in
which the heat from a pilot causes differential longitudinal
expansion between the two sides of a tubular metallic
element. This causes a small curvature of the tube which
is used to operate a valve. These devices have not been
used to any great extent, again due to the need for a gas
relay to control a reasonable gas flow.

2.3   The Thermoelectric F.F.D.

This has now become the most popular type of F.F.D. due
to its simplicity, ease of manufacture, relatively good
reliability and high flow capacity. Figure 1 shows a
drawing of a typical device. The thermocouple itself
consists of a stainless steel sheath with a constantan
wire inserted down its centre, the two being welded
together at one end to produce the hot junction. At its
other end the stainless steel sheath is brazed to a
copper tube, and the inner constantan wire welded to a
copper wire, which runs up the centre of the tube. The
copper wire and tube are separated by glass fibre insulation,
and thus form a low resistance coaxial conductor which can
be readily bent without causing a short circuit.

A typical thermocouple produces a minimum open circuit
E.M.F. of 25 m.V. at a hot junction temperature of $600^{o}C$ (12).
This voltage although small, is enough to power a small
electromagnet providing the circuit resistances are kept
low, and this effect is used to operate a F.F.D. Figure 1
shows a common type of valve assembly, in which both the
main burner and the pilot are protected by the F.F.D. The
thermocouple normally has a resistance between $10m\Omega$ and
$25m\Omega$ (12) and the electromagnet resistance is typically
$16m\Omega$, giving a total circuit resistance of approximately
$40m\Omega$. Therefore when the hot junction is heated by a
pilot flame, a current in the order of 600 mA will flow,
which enables the coil to hold a gas valve open against

a spring. If the supervision burner should extinguish,
the thermocouple will cool, and the circuit current will
gradually fall to below the holding current (~100 mA),
when the spring will shut the valve. The thermocouple
cannot supply sufficient energy to open the valve auto-
matically, so the valve has to be held open manually
by means of the reset button (fig. 1) until the thermo-
couple produces sufficient current for the magnet to hold
the valve open. This F.F.D. has a great advantage over
the bimetallic device in that the connection between the
flame sensor and valve is flexible, allowing a standard
device to be marketed, which can be bent to fit most
burner configurations. In some instances the device is
modified so that the electromagnet operates a switch,
enabling the device to be used in electric boiler control
systems, however this device still needs to be manually
reset.

The main drawback to the thermoelectric F.F.D. is the need
to manually reset the device on start-up. In appliances
where standing pilots are permitted (e.g. boilers) this
is not too great a problem as the pilot only needs to be
relit very occasionally, but in gas cookers where standing
pilots are not permitted this is a major disadvantage.
Reliability has also been a problem when sensing standing
pilots, as the long periods at high temperature result
in atmospheric oxygen diffusing through to the hot junction
causing it to oxidise. This causes the thermocouple
resistance to rise, resulting eventually in complete
failure of the device.

Thermoelectric F.F.D.'s are now the subject of a
British standard (13), as well as a draft European standard
(14).

2.4 The Mercury F.F.D.

The search for a better means of flame detection led to the

development of mercury vapour F.F.D.'s in the U.S.A.
during the 1940's. The patent for the first practical
mercury device was applied for in 1947 by C.A. Cobb of
the Missouri Automatic Control Corporation (now White
Rodgers) (15). A drawing of this device is shown in
fig. 3. It consisted of a phial filled with mercury
connected via a capillary tube to a chamber, one wall of
which was a flexible metal diaphragm. When the phial was
heated by a pilot flame the mercury within it boiled and
the resulting pressure forced mercury along the capillary
into the chamber. This caused the flexible diaphragm to
deflect, and operate a switch. When the flame was removed
the phial cooled, and the mercury vapour condensed causing
the internal pressure to drop thereby allowing the
diaphragm to return to its rest position and open the
switch contacts. Although Cobb (15) suggested that any
liquid might be used he noted, "Experiments indicate
mercury to be the preferred liquid, because it is stable
at high temperatures, it is heavy and gravitates well to
the opening in the lower end of the bulb chamber, and
because its boiling point is high enough so that heavy
loading of the spring is not required to maintain the
operating temperature of the device safely above tempera-
tures which may occur ambient to a burner in a furnace".

The volume of the phial and the capacitance of the
diaphragm (the volume increase per unit pressure increase:-
$\frac{\Delta V}{\Delta P}$) were fixed so that at its operating temperature the
phial contained only mercury vapour. This limited the
maximum deflection of the diaphragm, as once the phial
was emptied of mercury, heating to higher temperatures
would only result in small pressure increases as expansion
of the mercury vapour obeys the gas laws. Thus the phial
volume controlled the maximum diaphragm deflection, and
the device would not be damaged by overheating the phial.
Cobb also stated that by restricting the liquid - vapour
interface to the capillary, the pressure surges caused by
explosive boiling would be minimised.

This device seemed an ideal answer to the flame monitoring problem. Unlike the thermoelectric device it needed no manual resetting, as it was activated merely by the application or removal of heat from the flame sensing phial. Unlike the bimetallic device there were no exposed working parts which could be tampered with, and the moving parts were well removed from the source of heat so were less likely to become jammed due to oxidation. Another important point was that like the thermoelectric device there was a flexible connection between the sensor and valve part of the device, meaning that the device would not have to be engineered as part of the burner as with bimetallic devices. This mercury device was extensively fitted to boilers and clothes driers in the U.S.A., and is still manufactured albeit with small modifications by the White Rodgers Company.

The Cobb device had one drawback, it was a "flame switch", so to control a gas burner it needed an electricity supply, and a solenoid valve. During the 1950's further work was directed towards producing a mercury device which directly operated a valve rather than a switch. The Robertshaw Controls Company of the U.S.A. developed a solution, and a patent was applied for it by V. Weber in September 1958 (16). A drawing of this device is shown in Fig. 4. In Weber's device the phial and capillary were made from a wide bore tube closed at one end, with a shorter filler wire inserted from the other end. The chamber - diaphragm arrangement of the Cobb device was substituted by a capsule consisting of two flexible diaphragms welded together. This enabled the maximum safe deflection available from a given diaphragm diameter to be approximately doubled. As before, mercury in the phial boiled when placed in a flame and the pressure increase caused the capsule to deflect. As the capsule deflection was not sufficient to give an adequate valve lift by itself, the movement was magnified by a double lever system which operated the valve.

Weber's device was ideal for gas oven control systems,
as it operated entirely from flame energy, was potent-
ially very reliable, and had a flexible connection between
sensor and valve allowing one F.F.D. design to be used in
a variety of burner configurations. As a consequence of
these advantages, this type of F.F.D. has become the most
common to be fitted to cookers in the U.S.A., Canada and
Britain. Since the Weber patent (16) was applied for,
further U.S.A. patents were granted (refs. 17 - 23),
showing various ways in which mercury F.F.D.'s could be
combined with burner control systems.

The Weber type of mercury F.F.D. was expensive to produce
due to its complexity, and the need for accurate construc-
tion. Since the 1950's advances in the materials and
methods of production of flexible capsules have enabled
the maximum defections available to be increased from
approximately 0.4 mm to 0.9 mm. This has made possible
simpler direct acting devices which are cheaper to produce.
Figs. 5 and 6 show such a device, made in the U.K. by
Harper Wyman Ltd.

CHAPTER 3

PRESENT DAY USE OF MERCURY F.F.D.'S

3.1 Limitations of Mercury F.F.D.'s

The wider use of mercury F.F.D.'s in gas appliances other than cookers has been limited by the poor performance of these devices in the following three areas:-

3.1.1 Limited Flow Capacity

The maximum flow capacity of a typical mercury F.F.D. is in the region of 1 cu. metre per hour at a pressure drop of 0.75 mb. This has prevented such devices being extensively used in industry, where appliances generally require much higher gas flows. For this same reason the device has not been used in domestic central heating installations, which typically use gas at the rate of 1 to 3 cu. metres per hour, and in instant water heaters which have similar consumptions. Thus these large domestic markets have been taken over by thermoelectric and bimetallic devices which can handle larger gas flows.

3.1.2 Slow Response

A typical mercury F.F.D. takes approximately 30 to 60 seconds to respond to the application or removal of a flame, a response time similar to that of the bimetallic and thermoelectric devices. This is not important in domestic appliances with low gas consumptions, but is a serious fault in large industrial plant where vast volumes of unburnt gas could be liberated in this period. Thus industrial appliances have mainly been the province of electronic F.F.D's which are much quicker in response. (10)

3.1.3 Limited Life

The comparatively short life has proved to be a serious

problem when mercury F.F.D.'s are used to sense standing
pilots. The constant presence of hot mercury results in
dissolution and deposition of metal from the phial walls
(see section 4.2.1) causing blockage of the capillary
tubing. It is this fault which has limited the use of
mercury flame switches in domestic central heating
systems, where otherwise they would be an ideal flame
monitoring system.

3.2   The Gas Cooker Application

The ovens in British gas cookers normally have maximum
gas consumptions of less than 0.3 cu. metres per hour
(using natural gas), slow F.F.D. response is not a great
problem, and standing pilots are not used. Therefore
the mercury F.F.D. has proved to be ideal for this
application and in 1977 69% of British cookers were
fitted with mercury F.F.D.'s (24). In fact in Britain,
gas cookers form virtually the only market for mercury
F.F.D.'s, with only insignificant quantities being sold
for other applications.

Because of the importance of the cooker market, the
application of mercury F.F.D.'s in gas oven control
systems will now be considered in detail. Two basic
systems are used, the bypass type and the non-bypass type.

3.2.1 Bypass Type Mercury Systems

A typical installation of a bypass mercury F.F.D. is
shown schematically in fig. 7, this system being used in
the simplest and cheapest of gas cookers. The thermostat
has a dual role as it also incorporates a shut-off valve,
thus when the thermostat is turned on it allows gas to
flow to the F.F.D.. Since the flame sensing bulb is
normally cool when starting up no gas would ordinarily
flow through the device. A bypass orifice is therefore
fitted to the F.F.D. to permit a given flow rate of gas to

pass through to the burner whilst the valve is shut. In
the United Kingdom these bypass rates must be not greater
than 600 W equivalent gas rate (25), although in other
countries such as the U.S.A. much lower values are insisted
upon. In this way gas passes to the main burner at the
bypass rate, and is ignited by either a spark, or in some
cases a hot wire. Before 1976 standing pilots were often
used to give the ignition, but are not now permitted by
British Gas. The bypass gas produces a small bead of
flame on the main burner which heats the flame sensing
phial and after a delay of 30 to 60 seconds the flame
failure device opens. This allows the full gas flow to
pass to the burner and the flame to increase to full size.
The oven then heats up until the thermostat is satisfied,
when it gradually cuts back the gas flow to a maintenance
rate determined by a bypass orifice within the thermostat.
If in this reduced flame condition the burner should
blow out, the flame sensing phial would cool and the F.F.D.
would shut. Thus the full flow of gas to the burner is
prevented, although gas will always pass to the burner at
the F.F.D. bypass rate.

For more expensive cookers the system just described is
usually extended further by adding a timer, as shown in
fig. 7. When the cooking cycle is to start, the timer
turns on the gas supply to the F.F.D., and activates the
spark igniter. The system then operates as described
above, until the timer shuts off the gas supply at the
end of the cooking cycle.

3.2.2 Non-Bypass Mercury F.F.D. systems

These systems tend to be more costly and so are confined
to more expensive cookers. The problem with the bypass
system is that a large amount of bypass gas is needed to
produce a big enough flame on the main burner to open
the F.F.D., so if the flame should extinguish unburnt

gas will flow into the atmosphere at a high rate. A means
of overcoming this difficulty is shown in fig. 8. In this
case when the thermostat is turned on gas can reach the
F.F.D., but can go no further, since a bypass orifice is
not fitted. Gas is also permitted to flow to a timer
controlled valve. When the cooking cycle is to start the
timer opens this valve permitting gas to flow to the pilot,
which is then ignited by a spark generator also turned on
by the timer. The pilot heats the sensing phial and the
F.F.D. opens, allowing gas to pass to the main burner
which is ignited by the pilot. The thermostat controls the
main burner until the timer cuts off the gas supply to the
pilot. The F.F.D. then closes as the sensing phial is no
longer heated, and the main burner is extinguished. For
purely manual operation the timer can be over ridden, so
that the gas way from the thermostat to the pilot is
permanently open, and control of the spark igniter is
passed to the thermostat.

A pilot is a much more efficient way of heating the flame
sensor, as far less gas is needed than in the bypass/main
burner arrangement. If the pilot flame should be extinguished
during the operating cycle, only the low gas flow from the
pilot escapes once the F.F.D. has closed. Thus this
system is much safer than the bypass system. Another
advantage of using this system is that the main burner can
be throttled back to very low flame levels, by the thermo-
stat without affecting the F.F.D. This enables very low
oven emperatures to be properly controlled by the thermostat.
In fact the thermostat could turn the main burner off
completely, as the pilot would re-ignite the gas when the
thermostat reinstated the flow. This mode of operation is
commonplace in the U.S.A. but is not the practice in the
U.K., where a thermostat bypass is always provided. There
are two reasons for this, one being that the extinguishing,
and re-ignition of the main burner would cause an annoying
'pop' every so often. The other reason is that British

cookers are unique in that the user can see the main burner,
and this could deceive the operator if the main burner
was seen to be extinguished.

Because the non-bypass system needs a pilot and its
associated piping, it is more expensive than the bypass
system. Another cost increasing factor is that the F.F.D.
must be made to a higher specification to comply with
BS 5258 (25). This states that when a F.F.D. is required
to prevent the flow of gas under normal operating conditions,
the let by in the closed condition must not exceed 85 cm^3/hr
when tested with air, in the manner described in the
standard. For F.F.D.s only required to prevent flow
under conditions of flame failure (as in the bypass system)
the requirement is for a maximum let by of 3,000 cm^3/hr.
Clearly, making a valve, and testing it to this higher
standard, will add to its price.

CHAPTER 4

PROBLEMS WITH MERCURY F.F.D.'S

4.1 Mercury Health Hazard

In recent years the public have become much more aware
of the existence of poisons in the every day environment.
In particular, mercury has earned itself a bad name, due
partially to the famous incident of mercury poisoning
at Minamata in Japan (26). However this incident
involved the extremely poisonous alkyl mercury compounds
and not the far less toxic mercury metal. The public
unfortunately is unlikely to be aware of this distinction
and the prospect of a possible 'mercury scare' has
caused much worry in the gas industry.

Undoubtedly the symptoms of metallic mercury poisoning
are very worrying. Bidstrup (26) lists the classical
symptoms as including, "gingivitis and stomatitis,
accompanied by excessive salivation or a metallic taste,
erethism and tremor". Also listed are various non-
specific symptoms and signs such as "weakness, unusual
fatigue, loss of weight, pallor and disturbances of the
gastro intestinal function." The tremor can be sufficient
to make operations such as writing or drinking from a
cup very difficult. In serious cases kidney damage can
occur, which in rare instances has led to death. The
sensitivity of individuals to mercury poisoning seems
to vary, and in particular young children below the
age of 4 years can be very sensitive, developing an
illness called 'pink disease' from low exposures.

Mercury gains access to the body mainly through the
respiratory tract, but can also be absorbed through the
skin or by ingestion. Thus mercury contaminated air
is one of the main causes of the illness. Bidstrup
states that the accepted threshold limit is 0.1 mg
per cu. metre of air, and at room temperature air

saturated with mercury vapour contains 10 mg per cu. metre.
Goldwater (27) has pointed out that spilt mercury tends
to break into tiny droplets with a vast increase in
surface area giving a high evaporation rate. Spilt
mercury is notoriously difficult to clean up as it does
not wet most surfaces, and forms small mobile droplets.
Attempts to remove these make them roll away and enter
small holes and cracks, from where they continue to
contribute to the mercury burden in the air, but cannot
be removed.

Mercury F.F.D. thermal systems (the capsule, capillary
and phial) have been known to develop leaks in service,
usually because of a capsule failure, or a crack in the
phial (see table 3). A capsule leak, providing the valve
failed shut, and no mercury found its way into the
burner assembly and its piping, would not be a great
problem as the mercury would collect in the valve body
and be removed when the F.F.D. was replaced. A phial
leak is much more serious as mercury would be spilt into
the bottom of the oven, which could well be at high
temperature. Any attempt to clean up this spilt mercury
would undoubtedly leave traces behind which would gradually
evaporate.

However it must be stated that the amount of mercury
contained in a F.F.D. is very small, typically less than
1 gram, and that there has never been a case of mercury
poisoning of a member of the public which could be
attributed to one of these devices. The real worry
within the industry is that if the public were to discover
that mercury is used in gas cookers, the likelihood of
bad publicity could result in loss of sales to electric
cookers.

One group of people who are at risk though, are the people
involved in the filling of mercury thermal systems. These

are filled in trays in a vacuum chamber, and during
loading and unloading of these trays the worker comes
into contact with mercury. The process uses large quant-
ities of mercury, and occasional accidents can result in
mercury spillage. The thermal systems after filling are
sealed, a process which involves either T.I.G. welding of
the flattened phial end, or the spot welding of a ball
into a specially shaped filling hole (see fig. 5). Both
processes cause heating of the mercury which results in
vapour emission. There are many cases (26) of workers
using mercury under similar conditions in other industries
developing mercury poisoning symptoms, and the occurrence
of such incidents cannot be ruled out in this industry.
An awareness of such a danger has led to regular medical
checks for all workers at Harper Wyman Ltd. who come into
contact with mercury.

4.2 Reliability

Table 3 presents mercury F.F.D. field failure data for
the period up to March 1977, (28) which together with
laboratory test data published by Wharf (29) and re-
produced in table 4, suggests that mercury F.F.D.
reliability is not what it should be. This is especially
bad when one considers that the conditions for a mercury
F.F.D. fitted in a cooker is not particularly arduous.
British Gas (29) assume for the purposes of reliability
estimation a design life of ten years, during which only
3,000 cycles will be completed. Tables 3 and 4 show
that there are 3 major failure modes specific to the
mercury F.F.D., which between them account for most
failures in service. They are:-
     (1)   blockage due to phial leaching
     (2)   capsule failure
     (3)   phial leakage.
These are examined in detail below.

4.2.1 Blockage and Phial Leaching

A phial material must be able to contain hot mercury,
and resist an external oxidising environment. For
this latter reason the choice of materials is limited
in practice to stainless steels. Fig. 9 taken from
Weeks work (30) shows the solubilities of various metals
in hot mercury. It will be seen that nickel has a high
solubility, and for this reason British F.F.D. manu-
facturers have avoided austenitic steels and used ferritic
stainless steels, either of A.I.S.I. type 446 or 430 for
the phial. However as fig. 9 shows both chromium and
iron have appreciable solubility in mercury, and this
has given rise to problems in F.F.D.'s subjected to long
service. Fig. 10 shows the internal surface of a phial
which has been in use. The deposited material on the
inner surface can be seen quite clearly. This material
if deposited in the capillary could cause blockage, a
possibility which has been found to be happening in
practice. British Gas (31) report of a device which had
completed 7,800 hot/cold cycles on a test rig and had
become very slow in operation. The phial was sectioned
and examined. Iron deposited from solution in the
mercury was found all over the inner surface, and regions
of chromium deposition were found, which were thought
to have caused a blockage resulting in the slow operation.

The mechanism which has been suggested (32) for the attack
on the phial, and precipitation of material is as follows:
At the running temperature a stable liquid-vapour inter-
face (there can be two interfaces) forms at a point in the
phial which is determined by the temperature gradients
existing within the phial, and its inclination. At this
surface mercury laden with solutes is continually boiling, .
and hence the solutes are precipitated here. Above the
interface mercury vapour condenses on the cool parts of
the phial. Weeks (30) states that the erosion rate of
a metal in mercury is proportional to:-

$$S_o - S_i$$

Where S_o is the metal solubility and S_i is the concentration of the metal already in solution. For newly condensed mercury S_i is clearly zero, thus erosion rates will be proportional to S_o, values of which are indicated by fig. 9.

The temperature at which this solvent attack takes place is the boiling point of mercury at that particular pressure. (See fig. 9). Thus as the capsule stiffness increases, the erosion and deposition rate also increases, as the solubilities increase with temperature. (See fig. 9). Therefore this problem could be reduced by using more flexible capsules. Another suggested solution (33) was to reduce the amount of chromium in the steel, or use an iron phial with a chromized exterior. A typical F.F.D. (Harper Wyman type 5920) operates at a pressure of around 830 kPa at which the boiling point of mercury is 510 $^{\circ}$C. Reference to fig. 9 will show that at this temperature the difference in solubilities between iron and chromium is small, and a reduction in operating pressure would probably result in iron being more soluble than chromium. Thus even the use of pure iron phials would not offer a solution to the problem. Another conceivable answer would have been the use of a wide bore capillary tube, thereby making blockage an unlikely event, but as these devices need a restriction in the system to function correctly, this is not possible. Explosive boiling of the mercury has always been a problem (Cobb (15) noted this) because of the violent pressure fluctuations it causes in the thermal system, resulting in rapid variations in the capsule deflection, which produces unstable valve openings, creates noise, and in severe cases could cause early fatigue of the capsule. To avoid this happening it is usual to place a restrictor in the system to damp out these pressure fluctuations. The restriction is either a very narrow capillary, or a capillary flattened slightly at one point. In some

cases a metal 'slug' is placed in the phial which also
acts as a restrictor. As workable devices always need
some form of restriction the danger of blockage is always
high. Even if the restrictor is remote from the phial
there is always a danger of loose particles of deposited
material being carried to the restrictor and causing
blockage.

Hence in any mercury device subjected to long use,
blockage due to phial material deposition will be
a problem, and it is for this reason that mercury F.F.D.'s
cannot be used to sense standing pilots. The only way to
alleviate the problem is to fit a more flexible capsule,
and to try to arrange for the liquid vapour interface
to be at a place in the phial such that any deposition
of material occurs where it cannot cause a blockage.
Even so it is doubtful if a mercury device could be
made sufficiently reliable to sense a standing pilot.

4.2.2   Capsule Failure

Capsule failure would appear to be a relatively common
occurrence. British Gas field failure data (table 3)
has shown that up to 1977, 4.5% of all mercury F.F.D.'s
would fail in this way during their 10 year life. Wharf
(29) reports of experimental work done at Watson House
(see table 4), in which 230 mercury F.F.D.'s were sub-
jected to a 7½ minute hot, 7½ minute cold cycling. It
was found that of a total of 19 failures, 12 were due to
"bellows rupture".

Cracking of the capsule is caused by fatigue due to the
repeated flexing of the capsule. However a 3,000 cycle
life is not long in terms of fatigue, and failures within
this lifetime are due to a mixture of bad design and
poor manufacture. Bad design is a major element in these
failures, as in many current designs the very high
capsule "strokes" produced when the phial is heated result

in very high cyclic stresses which lead to a low cycle
life. Also in some designs the welds fixing the upper
and lower bosses to the diaphragms can act as stress
raisers, lowering the fatigue life. Poor manufacture
includes such faults as bad diaphragm edge welding, poor
top and bottom boss welds, poor material, and marks on
the diaphragms which act as stress raisers.

It is also possible that mercury attack reduces the
fatigue life of the 302 stainless steel capsules. The
reduction in fatigue life is very pronounced in brasses
and some aluminium alloys (34) but seems to be less so
with stainless steel. Rostoker et al (34) report only
a slight reduction in the fatigue life of 17-7 PH steel
when wetted with mercury. For any effect at all to be
produced the mercury must wet the capsule surface, which
entails removal of the extremely tough oxide layer on the
stainless steel. Abrasion effects are a usual cause of
such a happening, and it is conceivable that friction
between the two nesting capsules, as they move relative
to one another could cause oxide removal.

Table 4 shows that a significant percentage of capsules
develop a permanent set. This is a potentially dangerous
failure mode as it can result in the valve being held
permanently open. The problem is caused by the very
high stresses mentioned above, and where capsules developed
permanent set the stresses were sufficiently high to take
the material past its yield stress. Again this is a
design problem, but it is compounded by the choice of
302 stainless steel for the diaphragms, a material
which can only be hardened by the work done in forming
the diaphragms, and thus is restricted to quite low yield
stresses ($\sim$900 MPa).

4.2.3 Phial Cracking

It was indicated in section 4.2.1 that the need to keep phial leaching down to a minimum had dictated the use of ferritic stainless steels of A.I.S.I. type 446 (16-18% Cr), or 430 (23-27% Cr). These materials can suffer from embrittlement after extended service at high temperatures. Three embrittlement mechanisms are responsible:-

(a) '475 $^{\circ}$C' embrittlement due to the precipitation of a chromium rich (a prime) phase (35). This causes an increase in hardness and a reduction in izod impact energy. The maximum hardness increase is noted at 475 $^{\circ}$C (hence the name), and is made greater by increasing the chromium concentration. Generally steels containing less than 15% chromium do not exhibit this effect.

(b) Sigma phase embrittlement. This phase forms at temperatures above 500 $^{\circ}$C (35), precipitating first at the grain boundaries. The presence of the sigma phase increases hardness and reduces notch toughness. The problem is encountered with steels containing more than 15 to 20% chromium.

(c) Mercury embrittlement. It was noted in section 4.2.2 that mercury can reduce the fatigue life of metals. An allied problem is the mercury embrittlement of metals, in which mercury attack reduces the failure stress to below the yield point resulting in brittle failure. This is caused by intergranular attack on the metal by the mercury, which produces cracks which propagate easily. Mercury embrittlement is contingent on the mercury penetrating the surface oxide of the metal, which in the case of F.F.D. phials is known to be happening due to the solution attack. This phenomenon is well known in brasses and aluminium alloys, but Rostoker et al (34) report no embrittlement of mild steel at 30 $^{\circ}$C by mercury. However the mercury in a F.F.D. phial is at high temperature (approx. 500 $^{\circ}$C) for long periods, and thus a slow

embrittlement process cannot be ruled out. British Gas
(31) in their examination of a used mercury F.F.D. found
a region of subsurface attack on the inside of the phial
where once the surface had been penetrated, usually along
a grain boundary, attack proceeded along well defined
regions, one or two grains from the surface. This could
possibly have been an early stage of a slow mercury
embrittlement process.

A phial's operating conditions may be such that the hottest
point is at around 800°C, thus exposing the steel to a
range of temperatures from this high value down to room
temperature. Both 475°C, and sigma phase embrittlement
are therefore possible, combined with mercury embrittlement,
and thus it is not surprising that severe embrittlement
has been found in practice. Tests (36) have shown that
embrittled phials could be broken by hand force, and thus
impacts due to servicing or cleaning the cooker could
easily cause breakage, as is evidenced by the 5% of mercury
F.F.D.'s returned to British Gas with signs of phial
cracking (table 3).

Table 3 shows that 0.4% of returned F.F.D.'s had leaked
from the phial closure weld. Such failures occur with
designs which are filled from the phial end and are then
flattened and sealed by T.I.G. welding. Mercury if
present in the weld area can evaporate producing bubbles
in the weld which lead to early failure.

CHAPTER 5

THE FEASIBILITY AND MODELLING OF AN ALTERNATIVE F.F.D.

5.1 Features required by a new F.F.D.

In Chapter 4 the problems concerning the mercury F.F.D. were outlined. Two problems were fundamental, the fact that the devices contained toxic mercury meant that a leak must always be regarded as a serious occurrence, and the attack on the stainless steel phial by the mercury limited the life of the component. Design modifications did not appear sufficient to solve these problems, and a new approach was needed. Any new device under consideration must be able to replace the mercury F.F.D. in its present day uses, (see chapter 3) and if possible it should be applicable to a wider variety of appliances. To replace the mercury F.F.D. any new device must satisfy the following requirements:-

(a) It must be cheap to make.

(b) It must be self contained and not need an electricity supply.

(c) It must open and shut automatically.

(d) It must have a flexible connection between the sensor and valve.

In order to be suitable for a wider range of appliances than the mercury F.F.D., any new device should also satisfy some of the following requirements:-

(e) It must be able to sense standing pilots without premature breakdown.

(f) It must have a high cycle life.

(g) It should have a high gas flow capability, if possible up to 3 cubic metres per hour at 0.75 mb pressure differential.

(h) It should have a faster response time than that of bimetallic, thermoelectric or mercury devices.

Reference to table 2, which reviews mechanical flame det-
ection methods, will show that none of the devices known
at present will adequately substitute for the mercury
device in requirements (a) to (d) listed above. Hence
there is a call for a completely new device which will
satisfy requirements (a) to (d) and if possible have some
of the desirable features (e) to (h) to give a wider market
appeal than the mercury valve.

Besides meeting these market orientated requirements, any
new type of F.F.D. must of necessity comply with the rele-
vant British Standards. The most important of these is
BS 6047 part 1 (13) issued in 1981 which covers "Flame
supervision devices for domestic, commercial and catering
gas appliances", part 1 being the "Specification for heat
sensitive type". The fundamental requirements laid down
by this document are as follows:-

1) The device must be fail safe, and cause no danger
   to persons or the surroundings.
2) It must operate correctly over its full range of
   nominal working pressure, and an ambient temper-
   ature range of 0 to 60 $^\circ$C, or wider limits if
   claimed by the manufacturer.
3) When air pressure of 1.5 times the maximum
   pressure declared by the manufacturer (but at
   least 50 mb for 2nd family gas devices, or at
   least 60 mb for 3rd family gas devices), is
   applied to the inlet connection of a closed F.F.D.
   (with the bypass blanked off if necessary) the
   let by should not exceed the following values:-

Nominal size R (inches)	Nominal size DN (mm)	cm^3/hr air
$< \frac{3}{8}$	<10	20
$\frac{3}{8}$ to 1	10 to 25	40

4) The F.F.D. should operate satisfactorily, or
   the valve of the device should be closed and
   remain closed after the flame sensor, as defined
   by the manufacturer, has been maintained at
   1000 $^\circ$C $\pm$ 50 $^\circ$C for 4 hours. Overheating may
   result in failure, but not failure to shut
   down, and rupture of the flame sensing element
   must cause closure of the F.F.D.

5) The F.F.D. must be capable of performing 6,000
   operations without failure. For this test the
   first 1,000 cycles must be at 60 $^\circ$C (or higher
   if claimed by the manufacturer), followed by
   1,000 cycles at 0 $^\circ$C (or lower if claimed by
   the manufacturer), and finally the last 4,000
   cycles must be completed at 25 $^\circ$C $\pm$ 5 $^\circ$C.

Further specifications for F.F.D.'s are set out in BS 5258
parts 1 to 12 (25) "Safety of Domestic Gas Appliances".
Each part of this specification covers one type of appliance
and states whether a F.F.D. is required and gives the
maximum opening and closing times permitted for the F.F.D.
These details are summarised in table 5.

In considering a new type of F.F.D. it is important to
take cognisance of the range of expertise available to the
F.F.D. manufacturing industry. Cooper (37, 38) in his
"Project NewProd" looked into the factors affecting the
success of new industrial products. He found that amongst
other factors, "technical and production synergy-prof-
iciency" was an important determinant of new product success.
Thus to design a new type of F.F.D. whose concepts and
production technology were not within the experience of
the industry would be to invite failure of the new product.
Therefore it is worth considering a device similar to the
mercury F.F.D., but filled with some non-toxic fluid.
Such a device would very likely fulfil requirements (a)
to (d) (above), and if in addition some of requirements

(e) to (h) were also fulfilled, a broadening of the
market for this type of F.F.D. would be possible.

5.2   A New Filling Fluid for Thermal Systems

The opening temperature of a F.F.D. must be such that
at any ambient temperature likely to be encountered in
an oven (or other appliance), the opening and closing
times are less than those specified by BS 5258 (table 5).
The optimum opening temperature will vary between
appliances, depending on the range of ambient temperatures
experienced by the F.F.D. and the running temperature of
the flame sensor, but for most appliances the optimum
F.F.D. opening temperature would be in the range of
200 $^{\circ}$C to 400 $^{\circ}$C.

Mercury boils at 1 atmosphere pressure (101.3 kPa) at
357 $^{\circ}$C and generally needs to be heated to approximately
400 $^{\circ}$C to develop sufficient pressure (~100 kPa gauge)
to operate a F.F.D.. However in some cooker applications
this 400 $^{\circ}$C opening temperature has proved to be rather
too high, as the small bypass flame has difficulty in
heating the phial sufficiently to give a reliable valve
opening. Thus it would seem that the choice of a lower
boiling point liquid might be advantageous and when the
application demanded it, the opening temperature of the
F.F.D. could be increased by raising the working pressure.
Water for instance boils at 100 $^{\circ}$C, but this temperature
could be raised by increasing the operating pressures.
For a temperature of 200 $^{\circ}$C the saturated vapour pressure
would be 1.55 MPa, at 300 $^{\circ}$C it would be 8.58 MPa, at
350 $^{\circ}$C it would be 16.52 MPa and 400 $^{\circ}$C is beyond the
critical point of water (39). Clearly in extending the
opening temperature much above the normal boiling point
the high pressures present design problems. The same
would apply to other liquids, as the increase in vapour
pressure with temperature is always very rapid. A
simplified form of the Clausius-Clapeyron equation,

which applies if the pressures are not too high and the
temperature is not too near the critical point, illustrates
how the rate of increase of vapour pressure varies with
temperature:-

$$\frac{dP}{dT} = \frac{LP}{RT^2} \qquad \qquad \ldots\ldots\ldots (5.1)$$

where P is the vapour pressure, T is the temperature,
R is the gas constant and L is the Latent heat of vapor-
ization, which is a function of T tending towards zero
at the critical temperature. For small temperature
intervals some way below the critical temperature, L can
be assumed to be a constant (40). Integrating this
equation gives the following approximate relationship:-

$$P = Po \exp\left(\frac{-L}{RT}\right) \qquad \ldots\ldots\ldots (5.2)$$

showing an exponential dependence of vapour pressure on
temperature.

Therefore low boiling point liquids such as water and
ethanol cannot be used and a liquid with a boiling point
of around 300 °C should be chosen, enabling a F.F.D. to
be constructed with an operating temperature variable
over the range 300 °C to 400 °C. In searching for such
a liquid, two problems were encountered. Firstly the
liquid must not solidify at normal temperatures (say
down to -10 °C) as this would prevent the device from
working. Secondly the chosen fluid must be able to
withstand very high temperatures, as phials can reach
800 °C when operating, and in order to meet the require-
ments of BS 6047 part 1, the filling fluid must be
capable of withstanding 1,000 °C ± 50 °C for 4 hours.
Liquid metals other than mercury are available, such as
sodium-potassium alloys and caesium-sodium-potassium
alloys which have melting points below 0 °C, but unfort-
unately their boiling points are higher than mercury

(e.g. 78% K-Na alloy boiling point 667 $^\circ$C, melting point -12 $^\circ$C). These alloys would be very dangerous to use, because of their explosive combustion in air when hot, and would attack the phial over a long period in the same way as mercury. Many compounds, both organic and inorganic have boiling points at around 300 $^\circ$C, but nearly all will decompose at the high temperatures encountered in the F.F.D. phial. Any tendency for the fill fluid to decompose and liberate gaseous decomposition products would be most dangerous and contrary to BS 6047 as the F.F.D. thermal system (the phial, capillary and capsule) could become pressurized, causing the valve to remain in a permanently open condition. As the filling fluid must withstand very high temperatures for a long period (greater than 3,000 hours), and also be able to tolerate a 1,000 $^\circ$C test for 4 hours and always fail safe, the use of these compounds as a filling fluid is effectively ruled out.

A further possibility considered was the use of a reversible reaction which would liberate gas at a certain temperature. The choice of compound need not be a liquid, as a solid substance could be packed into the phial. This concept has been used in refrigerator thermostats (41), where activated charcoal liberates or adsorbs nitrogen or carbon dioxide gas at a certain temperature. However such adsorption processes are essentially a low temperature phenomenon, and for a high temperature device a reversible chemical reaction would have to be used. Such a reaction would by definition liberate a fairly reactive gas, which would gradually react with the hot stainless steel phial. This would reduce the pressure in the device, resulting in its eventual failure.

The obvious attraction of using an elemental gas made it a first contender for investigation as a filling fluid for F.F.D. thermal systems. Such a gas would not suffer

from decomposition at high temperatures and an inert gas
would eliminate attack on the thermal system. The limit-
ation with a gas fill was that it would not exhibit the
high pressure changes with rises in temperature shown by
substances undergoing a phase change, since the pressure
of a gas at constant volume is proportional to the
absolute temperature. This limitation could well be
overcome by the large temperature changes which a F.F.D.
senses. As an example the ambient temperature in an oven
may be 200 ^{o}C and the phial running temperature could be
700 ^{o}C. This would mean that a 500 ^{o}C temperature rise
was available to operate the valve, which would be
equivalent to doubling the fill gas pressure at constant
volume. Of course in a workable device, the pressure
rise would be less than this as the thermal system
would have to do work in moving the gas valve. Such
a device, due to the steady rise in gas pressure with
temperature would have the advantage over the mercury
F.F.D. that it could be calibrated to open at any temp-
erature within the range of interest, i.e. 200 ^{o}C to
400 ^{o}C.

In principle therefore, it would seem that a gas filled
device could substitute for the mercury F.F.D., and also
have some useful advantages over it. The question which
requires an answer, however, is would a gas filled
thermal system have a sufficiently good performance to
operate a F.F.D.? The following sections examine the
theory of gas filled thermal systems to enable performance
predictions to be made.

5.3 Model of Gas Filled Thermal Systems

To predict how a gas filled thermal system will perform,
a simplified model is needed. A drawing of the proposed
model is shown in Fig. 11. This consists of a phial of
volume V_p, connected via a capillary to a capsule of
volume V_c.

As the pressure P (kPa absolute) in the thermal system
varies, the capsule extension b will vary also. The
capsule internal volume (V_c) is related to b, and for
the purposes of this model this relationship will be
defined as:-

$$V_c = \pi r^2 b S \qquad \dots\dots (5.3)$$

where r is the capsule's active radius, and S is a
constant. For capsules whose surfaces deform conically
when they are pressurized S would be ⅓, whereas for
capsules whose surfaces undergo a spherical deformation
it can be shown that for small values of b, S would be ½.
In fact this equation agrees quite closely with experiment
and corrugated diaphragms have been found to have values
of S close to ½. (See Newell (42) and section 7.6)

However equation (5.3) does show that when b is zero,
V_c will also be zero, but in reality all capsules, even
"nesting" capsules, have some residual volume at zero
extension. This residual "dead volume" will tend to
reduce the performance of the thermal system, as will
the volume inside the capillary tube. Thus, for the
purposes of this model, the residual capsule volume and
the capillary volume will be combined to give a total
"dead volume" U.

When manufactured the thermal system will be filled to
a pre-determined pressure. In the present work the
"fill pressure", P_f (kPa absolute), will be defined as
the pressure inside the thermal system when it is at
300 $^\circ$K, and when the capsule is in its normal unloaded
state. To enable performance calculations to be made
for a thermal system, a reference value for the amount
of gas contained within the system is needed. A
convenient measurement of this is what shall be called
the "Nominal Fill Pressure" P_n (kPa absolute) which is

defined as the pressure within the thermal system when
it is at 300 $^{\circ}$K and when V_c is zero. For thermal systems
which are filled to pressures less than or equal to
atmospheric, P_n will be equal to P_f, but for those with
fill pressures greater than atmospheric, P_n will be a
purely calculated quantity, related to the "fill pressure"
by the following equation:-

$$P_n = \frac{P_f \ (V_{co} + U + V_p)}{(U + V_p)} \qquad \ldots\ldots\ldots (5.4)$$

where V_{co} is the volume within the capsule at the fill
temperature and pressure.

When the phial is heated to a temperature of T $^{\circ}$K, the
gas within it expands, thereby increasing the pressure
of the whole thermal system. For the purposes of the
model it is assumed that only the gas in the phial is
at T $^{\circ}$K and that all of the gas in the rest of the system
is at the environmental temperature T_e $^{\circ}$K. As the pressure
P in the system rises the capsule extension b will increase.
As a first approximation the capsule extension can be
assumed to be proportional to the pressure, giving the
following relationship:-

$$b = X. \ (P - P_a - P_s) \qquad \ldots\ldots\ldots (5.5)$$

where X is the pressure sensitivity of the capsule and
P_a is the atmospheric pressure. Some capsules will not
start to deflect until a certain pressure has been exceeded,
and this "starting pressure" is represented by P_s in
equation (5.5). Certain capsule designs (see section 7.2)
come quite close to this ideal linear behaviour, but more
frequently (see also section 7.2) X is a function of b
which decreases quite rapidly as b increases. For capsules
exhibiting a low nonlinearity, an average pressure

sensitivity $\bar{X}$ can be calculated and used in equation (5.5) to give a reasonable approximation to the experimental performance. However for more non-linear capsules, the actual pressure-extension data must be used in any performance calculation in order to obtain predictions.

5.3.1 Variation of Capsule Deflection with Phial Temperature

As stated in the last section the gas within the phial is assumed to be at T $^\circ K$ and the rest of the gas in the thermal system is assumed to at T_e $^\circ K$. To calculate the pressures developed within the system when the phial is heated, an average temperature T_{ave} must be assigned to the gas in the thermal system.

From the gas laws, the masses of gas in each of the three parts of the system are:

$$M_p = \frac{P\ V_p}{R\ T} \qquad \ldots\ldots (5.6)$$

$$M_u = \frac{P\ U}{R\ T_e} \qquad \ldots\ldots (5.7)$$

$$M_c = \frac{P\ V_c}{R\ T_e} \qquad \ldots\ldots (5.8)$$

where M_p, M_u, and M_c are the masses of gas in the phial, dead volume and capsule respectively. The average gas temperature will be given by:

$$T_{ave} = \frac{M_p\ T + T_e\ M_u + T_e\ M_c}{M_p + M_u + M_c} \qquad \ldots\ldots (5.9)$$

Substituting (5.6), (5.7) and (5.8) in (5.9) gives:-

$$T_{ave} = \frac{T \, T_e \, (V_p + U + V_c)}{V_p \, T_e + T \, (U + V_c)} \qquad \ldots \ldots (5.10)$$

Now that an expression for T_{ave} has been obtained, P, the system pressure can be calculated from the gas laws:-

$$P = \frac{P_n \, (V_p + U) \, T_{ave}}{300 \, (V_p + U + V_c)} \qquad \ldots \ldots (5.11)$$

where P_n, the nominal fill pressure, is the pressure when the entire system is at 300 ^{o}K, and when V_c is reduced to zero. From (5.10) and (5.11):-

$$P = \frac{P_n \, T \, T_e \, (V_p + U)}{300 \, [V_p \, T_e + T \, (U + V_c)]} \qquad \ldots \ldots (5.12)$$

When considering thermal systems with capsules whose performance is linear, a relationship between b and T can be obtained as follows:-

from (5.5)
$$b = X \, P - X \, (P_a + P_s) \qquad \ldots \ldots (5.13)$$

Substituting (5.12) into (5.13) gives:-

$$b = \frac{X \, P_n \, T \, T_e \, (V_p + U)}{300 \, [V_p \, T_e + T \, (U + V_c)]} - X \, (P_a + P_s) \quad \ldots \ldots (5.14)$$

For non-linear capsules, the actual pressure-extension function must be found experimentally, and combined with equation (5.12) to give a relationship between b and T.

5.3.2 The Thermal System as part of a Valve

When incorporated into a valve the thermal system is
arranged such that at a certain phial temperature T_s,
the capsule just starts to lift the valve plate off
its seat allowing the gas to flow. With a further rise
in phial temperature the valve lift h will increase
according to the equation:-

$$h = b(T) - b(T_s) \qquad \ldots\ldots\ldots (5.15)$$

where $b(T)$ and $b(T_s)$ are the values of b calculated from
(5.14) at temperatures T and T_s respectively.

5.3.3 Variation of T_s with Atmospheric Pressure and

Environmental Temperature

At the temperature T_s, at which the valve just starts to
open, equation (5.12) becomes:-

$$P = \frac{P_n \, T_s \, T_e \, (V_p + U)}{300 \left[V_p \, T_e + T_s \, (U + V_c) \right]} \qquad \ldots\ldots\ldots (5.16)$$

Rearranging (5.16) gives T_s as a function of P:-

$$T_s = \frac{300 \, P \, V_p \, T_e}{P_n \, T_e \, (V_p + U) - 300 \, P \, (U + V_c)} \qquad \ldots\ldots\ldots (5.17)$$

The valve will just start to open when the extension of
the capsule exceeds a certain value, at which the differ-
ential pressure existing between the inside and outside
of the capsule is always constant. Thus if the valve is
set to open when the internal pressure inside the thermal
system is P_i, and the atmospheric pressure changes by
an amount ΔP_a, then the valve will open at a different

internal pressure $(P_i + \Delta P_a)$. Because of this T_s will change to a new value given by the following equation:-

$$T_s = \frac{300 \, V_p \, T_e \, (P_i + \Delta P_a)}{P_n \, T_e \, (V_p + U) - 300 \, (U + V_c) \, (P_i + \Delta P_a)} \quad \dots \dots (5.18)$$

Equation (5.18) also shows how a combined change in atmospheric pressure ΔP_a and ambient temperature T_e will affect the opening temperature T_s. From this equation, the maximum range of ambient conditions can be determined, for which a given design of valve would be suitable, providing the maximum and minimum value of T_s has been decided, then equation (5.18) can be solved to find the limits to which ΔP_a and T_e can be taken both individually and together.

5.3.4 The Effect of Springs

In designs of F.F.D. where the valve plate is normally held shut by a spring, the capsule will have to overcome the spring force in order to open the valve. Since the movement of valve plates will be very small ($\sim$ .25 mm, see chapter 8) and as the springs used in a F.F.D. normally have a fairly low rate, the spring force (F) can be taken as constant. This spring force will increase the capsule starting pressure (P_s) to a new value given by:-

$$P_s = P_{si} + \frac{F}{A_e} \quad \dots \dots (5.19)$$

where P_{si} is the intrinsic starting pressure of the capsule and A_e is the pressure effective area, which is defined by:-

$$A_e = \left(\frac{\partial F}{\partial P} \right)_b \quad \dots \dots (5.20)$$

where F is the capsule force output caused by a pressure
P. Normally A_e remains reasonably constant throughout
the deflection and pressure range of the capsule, and
generally has a value of around 40% of the active capsule
area (42). Having calculated the modified value of P_s,
the performance of a spring loaded F.F.D. can be worked
out as before.

5.4 Computer Programs

Computer programs were developed from the model discussed
in section 5.3 to enable performance predictions to be
made for gas filled thermal systems. The BASIC language
was chosen for these programs, as this is the most common
language in use on the "mini computers" most likely to be
available to smaller manufacturing companies.

Two programs were developed; ffd.basic (see appendix 1)
which calculates the performance of a given system, and
var.basic (see appendix 3), which computes the effect of
ambient temperature and pressure changes on a thermal
system. These programs are described briefly below.

Figures 53 to 59 show performance predictions produced
by the programs. These predictions and the assumptions
underlying them are discussed fully in chapter 8.

5.4.1 ffd.basic

This program reads in capsule pressure-extension data
from a named file specified by the operator. The data
file must contain a series of points:-

$(0,0)$, (P_1, e_1), ... (P_m, e_m)

where e_m is the capsule extension (mm) at a given pressure
P_m (kPa). For a linear capsule only two points need be
supplied $(0,0)$ and (P_1, e_1), the first being the start
and the second marking the end of the pressure-extension

locus. This data is read into a matrix h (lines 400 to
510) by the program and the pressure calculation sub-
routine (lines 1200 to 1430) uses this data to calculate
the pressure z, at any extension b, by means of a linear
interpolation. For non-linear capsules, the pressure-
extension data file must contain more experimental points
and provision is made for up to 40 data points. The
program uses this data to approximate the true pressure-
extension curve to a series of short straight lines,
therefore the more data points read into the program, the
more accurate its predictions will be.

The thermal system parameters are then input by the
operator:- phial volume (v mm^3), capsule radius (r mm),
fill pressure (p kPa absolute), dead volume (u mm^3) and
finally start pressure (o kPa) (lines 270 and 280). The
program computes the nominal fill pressure (lines 520 to
730) and then goes on to compute the total capsule
extension and stroke at phial temperatures of 27 $^\circ$C,
50 $^\circ$C and then at 50 $^\circ$C intervals up to 800 $^\circ$C (lines
760 to 1100). This is done using an iterative process
at each phial temperature by first of all computing the
pressure (w) in the thermal system (lines 1210 to 1260)
at zero capsule extension (b) and comparing this to the
pressure (z) at zero extension calculated from the pressure
extension data contained in matrix h. The capsule exten-
sion (b) is then increased in 0.1 mm steps until z is
greater than w, when b is reduced in 0.01 mm steps
until z is less than w. The program then increases b
in 0.001 mm steps until z becomes greater than or equal
to w, and the value of b is then taken as the value of
the capsule extension at this particular phial temperature.
This iterative operation is repeated at each phial temp-
erature, and the computed performance data is placed in
a file "output" (see appendix 2 for a typical example),
which can be printed out if a copy is needed. Computed
data is also placed in a file "file31", which can be used
in conjunction with a graph plotting program to give a

direct graphical output. (See fig. 29 for an example).

5.4.2 var.basic

This program is based on ffd.basic and operates in
essentially the same way. Pressure extension data is
taken from a specified file and stored in the data matrix
h (lines 470 - 580), then as before the operator inputs
phial volume, capsule radius, fill pressure, dead volume,
and start pressure (lines 240 and 250). For var.basic
the temperature at which the valve is set to open, T_s
degrees C (called t in the program), must also be
specified. The program then goes through the iterative
proceedure described in 5.4.1 and computes the total
capsule extension at the phial temperature T_s for 10 $^{\circ}$C
ambient temperature intervals between 0 $^{\circ}$C and 150 $^{\circ}$C
(lines 590 - 920). Also calculated is the mean rate of
increase of capsule extension with ambient temperature
between 0 $^{\circ}$C and 80 $^{\circ}$C, 80 $^{\circ}$C and 150 $^{\circ}$C and over the
whole range 0 $^{\circ}$C to 150 $^{\circ}$C (lines 930 - 950).

The opening temperature of a gas filled F.F.D. would
normally vary with ambient temperature, therefore the
designer might wish to add some form of ambient temper-
ature compensation to a F.F.D.. All the data needed to
select the correct temperature compensation has now
been computed and having decided on a particular value,
the operator inputs this into the program (line 1100).
Starting with an ambient temperature of 0 $^{\circ}$C (line 1190)
and a phial temperature of T_s + 75 $^{\circ}$C (line 1180). the
capsule extension (b1) needed to just open the valve,
taking into account the temperature compensation, is
then computed (line 1240). The pressure (z) required
to give the capsule extension b1 is derived from the
pressure-extension data matrix h (lines 1250 - 1370)
and the actual internal pressure (z1) at this same
extension is calculated using equation 5.16 (line 1410).

z and atmospheric pressure are then subtracted from z1
(line 1420) to give z2, the change in atmospheric pressure
needed to produce a valve opening temperature of $T_s + 75\ ^{\circ}C$
at an ambient temperature of $0\ ^{\circ}C$. This is repeated for
values of ambient temperature from $0\ ^{\circ}C$ to $140\ ^{\circ}C$ in
$20\ ^{\circ}C$ steps. The whole process is further repeated for
T_s steps of $25\ ^{\circ}C$, in the range $T_s + 75\ ^{\circ}C$ to $T_s - 100\ ^{\circ}C$,
giving a total of 64 data sets which are stored in a
matrix C (lines 1200 - 1500). All of the computed data
is then placed in a file "voutput", which can be printed
out if a "hard copy" is required (see appendix 4 for an
example). The computed ambient temperature/atmospheric
pressure change/T_s data is also placed in a file "file32",
which can be used in conjunction with a graph plotting
program to give a direct graphical output (see fig. 58
for an example).

CHAPTER 6

THE PROBLEM OF GAS LOSS FROM THERMAL SYSTEMS

6.1 Diffusion through holes

In a study of the feasibility of gas filled thermal
systems, the question of leakage is of great importance.
The design life of a thermal system must be at least
10 years and as the quantity of gas contained is small
(about 500 mm^3), even a small leak will cause the
device to fail prematurely. Any hole present in a
pressurized thermal system will cause gas to be lost
at a rate proportional to the pressure differential
across it and varying inversely as the square root of the
molecular weight of the gas. Thus production techniques
must be sufficiently good to produce a thermal system
without any leaks. This is technically quite feasible
as exemplified by the production of evacuated aneroid
capsules for barometers and altimeters and the manu-
facture of refrigerant gas filled thermostats for
refrigerators (41). In these devices there must be no
appreciable ingress or loss of gas over a period of
many years, as this would seriously affect their accuracy.

Experience in the vacuum industry has shown that many
unavoidable leaks in metal walls are caused by porosity
in the steel. This porosity arises when the steel is
manufactured, and the forming processes which the steel
undergoes influence the direction in which the pores
run. Hence in the case of rolled steel strip, the pores
would run along the plane of the strip and, except in
very bad examples, leakage from one side of the strip to
the other would not occur. This also applies to tubing,
as the drawing process will make the porosity run in the
direction of the tube, thus there will be no leakage
from inside to outside. Therefore as the capsule will
be formed from stainless steel strip and the capillary
and phial will be made from tubing, the thermal systems

should have very few intrinsic leaks. The main leakage
risk will occur at welded or brazed joints and a good
design would reduce the number of these to a minimum.

Inevitably a certain percentage of thermal systems will
leak and these must be easily detectable in the prod-
uction process. One way of doing this would be to use
helium, or a mixture of helium and some other gas to
fill the thermal system. The sealed thermal system
could then be checked for any leaks with a helium mass
spectrometer. Commercial helium mass spectrometer leak
detectors are capable of detecting leaks as small as
10^{-10} Torr litres per second (43). Thus if for example
a thermal system of 500 cu. mm internal volume is filled
with pure helium and one assumes that failure has
occurred when the gas pressure has reduced by 10 kPa,
then the smallest detectable leak would be one which
caused failure after 15.6 years. Clearly when viewed
in terms of a ten year design life it can be seen that
mass spectrometer leak detection offers a sensitive means
of inspecting finished thermal systems.

Inspection of every thermal system by mass spectrometer
would probably not be feasible on the factory floor.
The value of this technique would be in quality control,
where say 1% of thermal systems produced are checked.
This ought to be adequate, since with mass production
techniques, faulty products will tend to come in batches,
due to wrong setting of production machinery, etc..

6.2 Gas Loss due to Reaction with the Thermal System Walls

Because of its working environment, the choice of material
for a gas filled thermal system is effectively limited
to stainless steels, most probably the "18-8" austenitic
type such as A.I.S.I. 321 which is readily obtainable

commercially. Any fill gas used must be totally inert
to this steel at the phial operating temperature, which
could be as high as 850 ^{o}C (see chapter 8 for a discussion
of phial operating temperatures), as any tendency to
react with the thermal system walls would cause a
gradual pressure drop. Stainless steels have the
benefit of a protective oxide layer, but in a phial
undergoing a thermal cycling regime this layer cannot
be relied upon to separate a reactive gas from the steel.

Of course the cheapest fill gas would be air, but even
under conditions of parabolic oxidation the oxygen
content would be gradually taken up as the oxide layer
on the stainless steel thickened. For example Mortimer
and Sharp (44) measured a weight gain of 0.15 mg/cm^{2} on
a 20% Cr ferritic steel after exposure to 1 atmosphere
of oxygen at 750 ^{o}C for a period of 40 hours. This is
equivalent to an oxygen uptake of approximately 0.1 cc
at S.T.P. per cm^{2} of surface area and if a typical phial
is assumed to have a volume of 0.5 cc and an internal
surface area of 4 cm^{2} (see chapter 8), then it will be
appreciated that the oxygen partial pressure would be
rapidly reduced.

An inert gas must therefore be chosen as a filling for
F.F.D. thermal systems. Nitrogen and carbon dioxide
are examples of cheap and what would normally be
considered fairly inert gases. However at the high
temperatures encountered in a phial, both of these
would react with stainless steel. Smith and Evans (45)
have found that 1 atmosphere of nitrogen would react
with a 20% Cr - 25% Ni - 1.5% Ti stainless steel when
heated at temperatures up to 1140 ^{o}C, forming precipitates
of CrN, Cr$_2$N, and TiN. Carbon dioxide is well known
to react with stainless steels (46), being reduced to
carbon monoxide leaving an oxide layer on the metal
surface. In some instances this reaction can proceed

further, the carbon dioxide being reduced to carbon which is then taken up by the metal.

Because of the danger of these reactions it is essential that the thermal systems be filled with a noble gas, such as helium or argon. With such a fill gas the danger of reaction with the phial walls would be completely ruled out.

6.3 Permeation

Permeation is the passage of a gas through the metal itself and generally the rate of permeation increases exponentially with temperature. So with the phial of a gas filled F.F.D. running at up to 850 $^{\circ}$C, there could possibly be a gradual loss of gas. This may well have been happening in the case of gas thermometers where, to quote The Instrument Manual (47), "It is found at the higher temperatures that certain metals become porous to gases, thereby lowering the pressure in the system. Some manufacturers, therefore, specify a maximum temperature of 800 $^{\circ}$F (427 $^{\circ}$C) for their products". A gas thermometer is similar to the device under discussion here, consisting of a phial, capilllary and a bourdon tube which operates a gauge giving a temperature reading. The thermometer is pressure filled with a gas, which is most usually nitrogen (47, 48).

The pressure dependence of the permeation of diatomic gases through metals has been generally found to comply with Henry's law (49, 50):-

$$\text{Permeation rate} = kP^{\frac{1}{2}} \qquad \qquad \text{.......} \quad (6.1)$$

where k is a constant and P is the pressure driving the permeant through the membrane. This finding indicates (from the law of mass action) that the gas does not pass

through the membrane as molecules, but that the gas molecules dissociate into atoms which then permeate the metal. Permeation is a far more complex process than diffusion through holes, and Shupe (51) has indicated 5 stages through which the gas must go to permeate a metal barrier.

1) Adsorption of molecules as atoms at the upstream surface.

2) Transition of the atoms from the adsorbed state to the sublayer immediately inside the upstream surface.

3) Diffusion of the atoms through the volume interior.

4) Transition of the absorbed atoms from the sublayer immediately inside the downstream surface to an adsorbed state on this surface.

5) Desorbtion from the downstream surface.

Any one of these steps, or a combination of several of them can be the rate limiting factor in permeation.

In stage 3 (above), the gas in solution in the metal diffuses through the metal wall, and the rate of diffusion will be given by Fick's law:-

$$J = -D \frac{\partial c}{\partial x} \qquad \qquad \dots\dots\ (6.2)$$

where D is the diffusion constant and $\frac{\partial c}{\partial x}$ is the concentration gradient. Clearly for mass transfer to be rapid, both D and $\frac{\partial c}{\partial x}$ must be large. In the steady state situation the maximum possible concentration gradient will be given by:-

$$\frac{\partial c}{\partial x} = \frac{s}{t} \qquad \qquad \ldots\ldots\ldots \ (6.3)$$

where s is the solubility of the gas in the metal and where t is the thickness of the metal wall.

Clearly then, in order to be able to permeate a metal membrane, a gas must be soluble in the bulk metal. However having a high solubility does not necessarily mean that a gas will permeate a metal membrane, as any one of the stages 1, 2, 4 and 5 mentioned above could limit the permeation rate.

Fortunately one group of gases are known not to permeate any metal at all, to quote Norton (49), "There seems to be one generalization: No rare gas permeates any metal. This has been tested over a large temperature range, and there has been no reliable report of the neutral rare gas showing any permeation through a metal wall". There are two reasons for this, the first being that the inert gases have been found to have undetectably low solubilities in metals (52). This is because the total free energy change when an inert gas dissolves in a metal is very positive, due to the positive lattice strain energy not being compensated for by any negative chemical binding energy. Therefore it is energetically very unfavourable for a noble gas to dissolve in a metal. The second reason concerns the first stage of permeation, the adsorption of the gas onto the metal surface. To be adsorbed, a gas must first undergo physical adsorption (53) where it is bound to the surface by Van de Waals forces. The binding energy is normally less than 8 K cal/mole and in the case of inert gases can be very low (e.g. argon on tungsten ~1.9 K cal/mole). Inert gases can only undergo physical adsorption and as the temperature is raised the physically absorbed inert gas will tend to desorb as the probability of an atom having

the necessary desorption energy increases. Reactive gases, however, can pass from a physically absorbed state to a chemisorbed state (53) characterized by a much higher binding energy, possibly up to 200 K cal/mole. Chemisorbed atoms will therefore remain on the surface at much higher temperatures, until they have sufficient activation energy to either desorb from the surface, or move into the bulk metal. Thus the chemisorbed state aids the transition of the gas from the atmosphere to solution in the metal, and the absence of this state is another barrier to the permeation of noble gases through metals.

Permeation rates of reactive gases through different metals have been measured by various researchers and a summary of results is shown in fig. 12. It will be noticed that in the examples shown in fig. 12, the permeation rate increased exponentially with temperature. This is not surprising since a permeating gas must surmount a series of energy barriers in going from a gaseous state to solution and vice versa and in diffusing through the bulk metal. The probability of an atom having sufficient energy to jump a barrier will increase exponentially with temperature and hence the permeation rate increases in a commensurate manner.

The choice of a noble gas to fill a F.F.D. thermal system would rule out the chance of any gas loss due to permeation. However permeation is a two way process and gas from the outside environment might permeate into the thermal system until the partial pressure of the permeant on the inside was the same as that on the outside. A phial in its working environment will encounter a range of gas mixtures, varying between:-

    a)   Air

        78% Nitrogen, 21% Oxygen (by volume)

b)   Unburnt gas - air mixture
     9.5% Methane, 18.9% Oxygen, 71.6% Nitrogen

c)   Burnt gas - air mixture
     9.5% Carbon Dioxide, 18.9% steam, 71.6% Nitrogen

From fig. 12 it will be observed that nitrogen has a
high permeation rate through iron, and in the three gas
mixture examples (above) nitrogen formed a large volume
fraction of the mixture. Thus the possibility of
nitrogen permeation must be considered, since for pure
iron the fill pressure of a device originally filled with
inert gas could rise by as much as 0.78 atmospheres
(79 kPa), which would seriously affect the F.F.D.'s
performance.

In practice, however, nitrogen permeation into stainless
steel thermal systems does not seem to occur, or at
least only occurs to a limited extent. Experimental
helium filled "18-8" stainless steel thermal systems
were run for several thousand hours at high temperatures
in a gas flame (see section 7-14) and in no case was
any measurable increase in fill pressure observed.
Mercury devices should also suffer from permeation, as
the manufacturing process leaves very little residual
air inside the stainless steel (A.I.S.I. 430) thermal
system. Thus when at operating temperature the partial
pressure of nitrogen in the phial would be very low and
if nitrogen permeation took place, the partial pressure
of nitrogen would gradually be raised to 0.78 of an
atmosphere (79 kPa). Fig. 13 illustrates the effect of
this magnitude of permeation on a Harper Wyman 5920
mercury F.F.D.. Line AC is a typical pressure -
extension line for the capsule and line DE represents
the point at which the valve is calibrated to open.
The case considered is where 0.78 atmospheres permeated
at a running temperature of 700 $^{\circ}$C. The curve represents
the way in which the pressure of the permeated gas would

vary with capsule extension when the whole thermal system
is at 27 $^{\circ}$C. It will be seen that at the point B where
the curve intersects the line AC, the valve is just
open, thus if permeation occurred to this extent all
valves would eventually be left permanently open. This
has not been known to happen and it can therefore be
assumed that permeation does not occur to any great
extent, so clearly nitrogen permeation through stainless
steel is much more limited than permeation through pure
iron.

At first sight this is very surprising, as nitrogen is
more soluble in stainless steel than in pure iron.
For example at 900 $^{\circ}$C, .0033 mass % of nitrogen can
dissolve in pure α iron (52), whereas in A.I.S.I. 304
(18% Cr - 8% Ni-Fe) stainless steel at 900 $^{\circ}$C, up to
0.25 mass % of nitrogen can be dissolved before nitride
precipitation occurs. For A.I.S.I. 430 steel (18%
Cr-Fe), the solution limit at 900 $^{\circ}$C is a little lower
than in 304, being 0.05 mass % (35), but this is still
more than for pure iron. At 700 $^{\circ}$C the situation is
much the same, pure α iron dissolving .0015 mass % of
nitrogen (52) and A.I.S.I. 304 stainless steel dissolving
approximately 0.1 mass % nitrogen (35). The reason for
this solubility difference is that iron (below 906 $^{\circ}$C)
has a BCC structure, whereas A.I.S.I. 304 stainless
steel has a FCC structure and therefore much larger
interstitial gaps. Therefore diffusion through the
bulk steel cannot be the rate limiting process, and one
of the other stages in the permeation process must be
the cause.

Eschbach et al (55) in studying hydrogen permeation
through stainless steel noted that "an oxide layer on
the membrane reduced the permeability markedly", and a
partial pressure of oxygen of a few torr in the hydrogen
was found to reduce the permeability by a factor of 10.

Simplistically a protective oxide on a stainless steel
will reduce the permeation since it forms a barrier
between the metal and atmosphere, and in the case of a
stainless steel phial running in a gas flame at red
heat the oxide layer would be far thicker than that in
Eschbach's work, and a far greater reduction in per-
meation would be expected in the F.F.D. phials.

Most metal oxides grow by the diffusion of metal ions
(cations) through defects in the oxide, to the surface
where they combine with oxygen from the air. This
happens because the majority of the defects in the oxide
lattice are cation defects, providing plenty of vacant
sites to aid diffusion of the cations. Stainless steel
has such an oxide and Hagel et al (56, 57) have measured
the diffusion constant (D) of the cation in Cr_2O_3 at
1100 $^{\circ}$C to be approximately 10^{-11} cm^2/sec, whereas
they found that the diffusion constant for the anion
was very much less, at 10^{-15} cm^2/sec. Because oxidation
is mainly a process of metal diffusing up through the
oxide to meet the oxygen, then atmospheric nitrogen
will not be able to come into contact with the bulk
metal, unless it can penetrate the oxide layer in some
way.

There are three possible mechanisms by which nitrogen
from the air could penetrate an oxide layer to reach
the metal surface. These are:-

1) Gaseous diffusion through cracks in the oxide
layer.
2) Diffusion of nitrogen via interstitial sites
in the oxide lattice.
3) Substitution of nitrogen ions for oxygen ions
in the oxygen sublattice and diffusion via a
vacancy or exchange mechanism.

If the stainless steel is at a temperature where the
oxide layer is fulfilling its protective role, any

cracks should heal over quickly due to the formation
of new oxide, thus the amount of nitrogen finding its
way to the metal surface via mechanism (1) should be
small. The probability of nitrogen dissolving inter-
stitially in the oxide is low due to the large size of
the ion (N^{3-} 0.92Å, O^{2-} 1.32Å, Cr^{3+} 0.63Å), therefore
very little nitrogen is likely to find its way to the
metal by means of mechanism 2. This leaves the possibility
of the replacement of oxygen ions by nitrogen ions, which
then diffuse through the oxide layer to the metal. This
is unlikely to happen to any great extent for two reasons.
First nitrogen ion substitution for oxygen ions is
unlikely unless the partial pressure ratio PN_2/PO_2
becomes very high, due to the much higher heat of
formation of Cr_2O_3 (-270 K cal/mole) than CrN (-29.4
K cal/mole). Thus the amount of nitride to be found in
a normal oxide layer is likely to be very small.
Secondly, it has been pointed out earlier that the
diffusion constant for oxygen anions is very low in
Cr_2O_3. If nitrogen ions in a layer of oxide on a
stainless steel were assumed to behave in a similar
manner, then the diffusion constant for them would be in
the order of 10^{-15} cm^2/sec at 1100 $^\circ C$ and 10^{-19} cm^2/sec
at 800 $^\circ C$. Table 6 summarizes diffusion constants for
ions in various media, and it will be noted that if the
assumptions made above are reasonable, then nitrogen
diffusion in a stainless steel oxide at 800 $^\circ C$ could
be up to 10^{12} times slower than nitrogen diffusion in
iron. These, then, are indications that an oxide layer
does indeed act as a very effective barrier to nitrogen
permeation.

Examination of table 6 suggests that oxygen permeation
would be fast, since D for oxygen in iron is close to
that of nitrogen at 800 $^\circ C$, and an oxide layer would
give a high concentration of oxygen ions at the metal
surface. This is not the case because oxygen solubilities

in metals other than those in group IV A and V A of the
periodic table tend to be very low indeed (58). Taking
pure α iron as an example, the solubility of N_2 at 800 $^\circ$C
has been measured at 2.3×10^{-3} mass % (52), whereas
the solubility of oxygen may be as low as 1.5×10^{-7}
mass % at 750 $^\circ$C (58).

6.4 Choice of fill Gas

Section 6.2 and 6.3 pointed out that only noble gases
could be used to fill F.F.D. thermal systems, as these
are the only gases which will not chemically combine
with the hot phial walls and which will not permeate out
of the thermal system. In section 6.1 it was suggested
that helium would be a good choice of fill gas as it
would enable leaks to be detected and also its high
thermal conductivity (some six times that of air) might
be an advantage. If helium were to prove too costly,
then argon could be used as a substitute.

It is suggested that a well made thermal system filled
with either of these gases would be able to sense a gas
flame for a long period of time, without any change in
the amount of gas it contained.

CHAPTER 7

EXPERIMENTAL WORK

7.1 Gas flow versus Pressure drop Measurements

The multi-purpose test rig shown in figures 14 and 15
was used to determine the gas flow rate through a valve
at different values of pressure drop and valve lift.
Nitrogen gas at a pressure of 1,000 kPa was fed to a
"Govenaire 1062" pressure regulator (R1), which
enabled the output pressure to be accurately regulated
over the range 15 to 1,000 kPa, the pressure being
monitored by a gauge, G1. A needle valve V9, allowed
gas to flow at a controlled rate to two "rotameter"
flowmeters F1 and F2. F1 covered a nitrogen flow range
of .04 to .3 cubic metres per hour and F2 measured over
the range 0.2 to 1.8 cubic metres per hour. Both
flowmeters were calibrated to an accuracy of $\pm 2\%$
indicated flow + 0.2% of the full scale reading. The
valves V6 and V7 enabled the correct meter to be
selected to suit the gas flow rate. From the flowmeters,
the gas passed via a 12 mm diameter pipe to the inlet
of the F.F.D. being flow tested. A pressure tapping was
taken 80 mm upstream from the union to which the
experimental valves were screwed and the pressure at this
tapping was measured by a gauge G2, scaled to read 0 to
5 mb to an accuracy of $\pm$ .05 mb. A "bubbler" relief
valve was provided to protect this gauge.

An experimental inconel X 750 capsule, similar to that
described in section 7.2 was brazed to a capillary tube
and a threaded stud was bonded to its top surface. The
pressure extension characteristics were measured by the
method outlined in section 7.2. The capillary and
capsule were bonded into a F.F.D. valve body (as in figure
32) and a valve plate was screwed down the stud until

the capsule was pulled lightly into tension. The valve
plate was locked in this position by the application of
cyanoacrilate adhesive to the screw thread. The resulting
valve was similar to that shown in figure 32, except that
the phial end was open allowing the capsule to be pressur-
ized. The inlet of this valve was screwed to the flow
test union on the test rig and the open end of the phial
was connected to the roving connector (see fig. 14).

The turbulent flow pressure drop (Δp) through such a
valve at gas velocities of less than mach 0.2 can be
expressed as:-

$$\Delta p = \rho F^2 (C_v + C (D,h)) \qquad \dots\dots\dots (7.1)$$

where ρ is the gas density and F is the flow rate at
S.T.P.. The bracketed term is the flow resistance of
the valve which can be split into two component parts,
C_v, the resistance due to the valve body and C (D,h),
the flow resistance across the valve seat which is
a function of its diameter (D) and the valve lift (h).

First the pressure drop due to the valve body was measured
in the following manner. The pressure regulator (R1)
was adjusted to give sufficient pressure to the capsule,
so that the valve plate just lifted off its seat. This
was indicated by the start of gas flow through the valve.
The capsule pressure was noted and the pressure was then
increased to give a valve lift of 0.75 mm (determined
from the previously measured pressure-extension curve).
The flow of gas through the valve was varied using V9
and the pressure drops measured using G2. These nitrogen
flow rates were converted to natural gas flow rates by
multiplying by 1.285 (the ratio $\rho N_2/\rho$Nat gas. See
equation 7.1). These high valve lift pressure drops
indicated the resistance due to the valve body and are
reproduced in fig. 16.

The capsule pressure was adjusted to give valve lifts
varying from 0 to 0.25 mm, the nitrogen flow rate varied
and the corresponding pressure drop-flow relationship
was measured for the different valve lifts. The pressure
drop due to the valve body at each particular flow (fig.
16) was then subtracted from the measured pressure
drop at that flow, to give the pressure drop due to the
valve seat itself. This pressure drop-flow-valve lift
relationship was plotted and the gas flow required to
give a valve seat pressure drop of 0.5, 0.75 and 1.0 mb
at the different values of lift were found by inter-
polation. These results are shown in fig. 17. Fig. 18
illustrates the leading dimensions of the valve seat
and valve plate used in this experiment.

7.2 Measurement of Capsule Pressure Extension Curves

The capsule was brazed to a capillary tube and the top
boss was ball sealed. The capillary was connected to
the roving connector on the multi-purpose test rig and
the capsule clamped into the capsule extension measur-
ing apparatus illustrated in fig. 19. The dial indicator
enabled capsule extensions to be measured to .0025 mm.

To measure the pressure-extension curve, the capsule
internal pressure was adjusted by means of the pressure
regulator R1 and the pressure measured on gauge G1,
(fig. 14), which was calibrated to measure 0 to 689.5 kPa
to an accuracy of ± 6.89 kPa. Several special capsules
were made for this work by Pressure Sensors Ltd. of
Axminster and Fig. 20 shows the (rising) pressure-
extension curve for one of them (capsule number 7).
These capsules were made from .075 mm thick inconel
X 750 and precipitation hardened. The active diameter
was 18 mm and there were 2½ sinusoidal corrugations
with an amplitude of 0.32 mm (peak to peak) and a
wavelength of 2.1 mm. It will be observed from fig. 20

that this capsule came very close to having a linear pressure-extension performance and a possible linear approximation is suggested in fig. 20.

Figs. 21 and 22 illustrate the measured (rising) pressure-extension curves of two 18 mm diameter Harper Wyman mercury F.F.D. capsules (capsules 4 and 31 respectively). These had .127 mm thick diaphragms made from A.I.S.I. 302 stainless steel, the dimensions of which are illustrated in fig. 23 (see also the section through such a capsule shown in fig. 24). It will be observed that the pressure-extension curves for these capsules were less linear than those of the inconel X 750 type. During the course of this work many of these Harper Wyman capsules were tested and a considerable variation in their pressure-extension characteristics was noted. The pressures needed to produce an extension of 1 mm varied between 470 kPa and 660 kPa, fig. 21 showing a very flexible example and fig. 22 illustrating a more average capsule.

The inconel X 750 capsules were found to exhibit no measurable hysteresis, however a considerable hysteresis was measured for the Harper Wyman capsules. The curves shown in figs. 21 and 22 were measured using rising pressures and higher extension readings were noted if the measurements were made with reducing pressures. Fig. 25 shows a hysteresis curve measured for a Harper Wyman capsule. Curve BCA was the difference between decreasing pressure readings and rising pressure readings and loop C-D-B-C shows the amount of hysteresis measured when the capsule was cycled between its full extension (at 586 kPa) and an intermediate extension (at 152 kPa).

7.3 Experimental Thermal Systems - Production and Testing

Experimental phial and capillary assemblies were con-
structed as shown in fig. 26. The phials were machined
from solid A.I.S.I. 304 stainless steel, two sizes
being made, which gave an internal phial volume of
either 300 mm^3 or 500 mm^3 when sealed. The phials were
brazed to the capillary using 'Nicrobraz LM', a
proprietary high temperature stainless steel brazing
alloy. The other end of the capillary was brazed to a
capsule, the pressure-extension performance of which was
measured as described in section 7.2.

The experimental thermal systems were filled with
helium and sealed by the method shown in fig. 27, the
sequence of events being as follows:-

a) The thermal system was placed in a hydraulic
press which was fitted with hardened steel jaws.
The phial was clamped so that the distance L (see
fig. 27) was the correct length to give the desired
phial volume. (24 mm for 300 mm^3 phials, 27 mm
for 500 mm^3 phials).

b) The capsule was clamped in the capsule extension
measuring apparatus to enable the filling process
to be monitored.

c) The filling pipe was fitted to the open end of
the phial by means of a quick release coupling.

d) V2 was shut, V1 opened and the system evacuated
to less than 10 kPa pressure.

e) V1 was then shut, V2 opened and the regulator
R1 adjusted to give the correct fill pressure
(measured by G2), or capsule extension (measured
by the D.T.I.) depending upon which criterion was
being used.

f) Steps (d) and (e) were repeated twice to ensure
complete removal of air from the system.

g) The hydraulic press was then operated so as to crush the phial. The press was set to give a force of approximately 5,000 kg, which temporarily sealed the end of the phial.

h) V1 and V2 were shut and the fill pipe was removed. The dial gauge on the capsule extension measuring apparatus was checked to see if there was any gas leakage.

i) The open end of the phial was packed with DRY 'Nicrobraz LM' and heated to orange heat with an oxy-acetylene torch. It was necessary to repeat this step once more to obtain a good braze seal.

j) The hydraulic press pressure was released and the dial gauge checked to see if the braze seal had leaked.

This method was capable of producing well sealed thermal systems. Unfortunately the success rate was never very high, particularly when using the larger diameter 500 mm^3 phials, when approximately 30% of seals leaked on removal of the hydraulic pressure. However this technique was adequate for producing a sufficient number of samples for experimental purposes, especially as most of the thermal systems successfully filled showed no tendency to leak later, even when subjected to arduous tests. A photograph of a completed thermal system with a 500 mm^3 phial is reproduced in fig. 28.

To measure the performance of completed thermal systems, a thermocouple was spot welded to the centre of the phial, which was inserted into a tube furnace and a digital thermometer was connected to the thermocouple leads. The phial was heated and readings of phial temperature versus capsule extension were taken for phial temperatures up to 700 $^\circ$C (going to higher temperatures than this risked melting the Nicrobraz seals).

Figs. 29, 30 and 31 show the measured values (crosses)
of capsule extension versus phial temperature for thermal
systems 7, 4 and 31 respectively (made using capsules
7, 4 and 31 - see section 7.2). After testing, thermal
system 7 was sectioned and its dead volume measured to
be 59 mm^3 ($\pm$5 mm^3). The phial volume was estimated at
300 mm^3 ($\pm$10 mm^3) and the fill pressure (Pf) was 260 kPa
($\pm$10 kPa) absolute. This data, along with the linear
approximation to the pressure extension curve ($\bar{X}$ =
2.28 x 10^{-9} m/Pa) shown in fig. 20, was used to produce
the computed performance prediction illustrated in
fig. 29.

Experience with thermal systems made using Harper Wyman
18 mm^3 diameter capsules has shown them to have a typical
dead volume of 60 mm^3 ($\pm$10 mm^3). The phial volumes of
thermal systems 4 and 31 were both estimated to be
500 mm^3 ($\pm$10 mm^3). The fill pressures for thermal
systems 4 and 31 were 278 kPa ($\pm$10 kPa) absolute and
266 kPa ($\pm$10 kPa) absolute respectively. Computer
predictions of performance were made using this data
and the measured capsule pressure-extension performance
and these are shown in figs. 30 and 31. The reason for
the discrepancy between the conputed predictions and the
measured performance is discussed in chapter 8.

7.4 Experimental Flame Failure Devices - Construction and Testing

The thermal system was first of all made and tested in
the way described in section 7.3 and was bonded into a
diecast F.F.D. body as shown in fig. 32. A threaded
stud was bonded to the top of the ball seal using epoxy
adhesive, the stud being held perpendicular to the
valve seat by a jig whilst the adhesive was setting.
The outlet of the F.F.D. was then screwed onto the flow
test union of the multi-purpose test rig. The phial was

instrumented with a thermocouple, placed in a tube
furnace and heated until it was at the temperature at
which the F.F.D. was intended to start opening. A
standard 25 mm diameter valve plate (see fig. 18) was
screwed onto the threaded stud until it came into light
contact with the valve seat, so that the valve was just
shut.

The water level in the 'bubbler relief valve' on the
test rig was set so that the dip tube end was 2.5 cm
below the surface and R1 and V9 (see fig. 14) were
adjusted (with valves V7 and V8 open) so that bubbles
escaped at a rate of approximately one per second from
the dip tube. The valve plate was slowly unscrewed,
until bubbles just stopped appearing at the end of the
dip tube, when the valve plate was locked in this
position by application of cyanoacrilate adhesive to
the screw thread.

After constructing the F.F.D. in this way, it was leak
checked. The phial was allowed to cool, valve V8 was
closed and needle valve V9 adjusted to give a reading
of 50 mb on the manometer. V9 was then closed and the
water column in the manometer was observed for any
gradual loss of pressure.

If the valve was leak free, the cover plate and rubber
gasket were fitted to the back of the F.F.D., which was
then taken off the flow test union. The inlet of the
F.F.D. was screwed onto the flow test union and the
instrumented phial was replaced in the tube furnace.
The phial was heated until the F.F.D. opened and R1
and V9 were adjusted to maintain a gas flow through the
valve which gave a pressure drop reading on G2 of 0.75 mb.
Readings of phial temperature against the nitrogen flow
rate at 0.75 mb pressure drop were recorded up to a phial
temperature of 700 $^{\circ}$C. Fig. 33 shows the flow-temperature

curve for F.F.D. number 31 (constructed from thermal system number 31), with the nitrogen flow rates converted to natural gas flow rates. Fig. 34 shows a photograph of a completed gas filled F.F.D. with a 500 mm^3 phial.

7.5 The Cooling Rates of F.F.D. Phials

The cooling rates of a 300 mm^3 and a 500 mm^3 experimental phial (made in the way described in section 7.3) were measured at an ambient temperature of 22 $^{\circ}$C. A thermocouple was spot welded to the centre of the phial which was supported 25 mm above a cooker type gas burner on the life test rig (see fig. 51), so that the thermocouple was in the centre of the flame, facing upwards. The burner was turned on and the F.F.D. phial was allowed to reach a stable running temperature. With the burner full on this was found to be 693 $^{\circ}$C for the 300 mm^3 phial and 690 $^{\circ}$C for the 500 mm^3 phial. The burner was turned off and readings of phial temperature against time were taken for a total of 4 minutes. Fig. 35 shows the cooling rate measurements for the 300 mm^3 and the 500 mm^3 phials.

A 30 mm long by 3 mm diameter mercury F.F.D. phial was also tested (results not shown in fig. 35). It was found to run at 795 $^{\circ}$C with the burner full on and cooled to 443 $^{\circ}$C in 10 seconds, 340 $^{\circ}$C in 20 seconds and 280 $^{\circ}$C in 30 seconds. This rate of cooling was very similar to that exhibited by the 500 mm^3 phial.

The cooling rate of a 300 mm^3 gas filled phial was also measured when it was placed above the burner in an oven at maximum temperature. The phial was instrumented with a thermocouple and supported 30 mm above the burner in a 'New World Conquest' gas oven. The phial was positioned so that the thermocouple was in the centre of the flame facing upwards. A thermocouple was also spot welded onto

each of two 9 mm diameter by 140 mm long stainless steel
rods. One of these rods was placed on the wire baking
shelf at the centre of the oven and the other was placed
at the centre of the oven floor, with the thermocouple
uppermost. The leads from these three thermocouples were
taken out through the oven door and insulated so that the
oven door could be closed on them without causing a short
circuit. The oven was set to gas mark 9 and left for
one hour. After this time the thermocouple at the oven
centre was reading 247 $^{\circ}$C (gas mark 9 is 250 $^{\circ}$C) and
the thermocouple on the oven floor was reading 146.5 $^{\circ}$C.
The F.F.D. phial temperature was found to have stabilized
at 660 $^{\circ}$C. The oven was then turned off and readings of
the phial temperature against time were taken for a
period of 4 minutes. These are shown in fig. 35.

7.6 Capsule Volume/Extension Measurements

The capsule to be tested was brazed to a capillary tube,
ball sealed and the pressure-extension performance was
measured as detailed in section 7.2. The capsule was
bonded into a valve body with ¼" B.S.P. connections
(as in fig. 32), the inlet of which was plugged so that it
was completely leak tight. The gasket and cover plate
were then fitted to the back of the body, as shown in
fig. 32. A hole was drilled in a ¼" B.S.P. plug and the
end of a 600 mm long, 1.2 mm bore glass capillary tube
was bonded into the plug using epoxy adhesive. The valve
body was completely filled with room temperature water,
great care being taken to remove all air bubbles from
inside the body. The ¼" B.S.P. plug with the glass
capillary tube was screwed into the outlet of the valve
body and the assembly was laid down so that the capillary
tube was exactly horizontal. The position of the
meniscus in the capillary tube was marked.

The capillary tube connected to the capsule was coupled

to the test rig's roving connector and the capsule
internal pressure was adjusted using pressure regulator R1
(fig. 14). Readings of the water column length in the
glass capillary tube were taken at different capsule
pressures. The water column lengths were converted to
volumes, the pressure readings converted to capsule
extensions (from the pressure-extension data) and the
resulting volume-extension relationship plotted.

Fig. 36 shows the volume-extension relationship for a
typical Harper Wyman 18 mm diameter capsule. It will
be observed that there was a linear relationship between
extension and volume as suggested by equation 5.3 (see
section 5.3). This gradient corresponded to a value
of S of 0.48. The same measurements were made for an
inconel X 750 capsule, of the type used to make thermal
system number 7, and again a linear relationship was
observed, which for this capsule corresponded to an S
value of 0.49.

The effects of force on the capsule extension-volume
relationship were also investigated. To do this, the
capsule pressure-extension performance was measured with
the capsule subjected to various central loads on the
top diaphragm. This was done by mounting the capsule
extension measuring apparatus vertically (fig. 19b),
adding weights to the top of the D.T.I. and then
measuring the pressure-extension relationship. The
capsule, capillary and valve body were assembled as
before, but this time a spring was arranged to restrain
the capsule with a load corresponding to one of those
used when measuring the loaded pressure-extension data.
A low rate spring was chosen to minimise the increase
in spring force as the capsule extension increased. The
valve body was filled with water and the volume-extension
relationship measured.

Fig. 36 shows the result of a 10N load on the volume-

extension relationship of a Harper Wyman 18 mm diameter capsule, It will be observed that the force had little effect on the gradient, but affected the intercept with volume axis. With no load a 2.5 mm^3 intercept was observed, whereas with a 10N load a 13.5 mm^3 intercept was obtained.

7.7 Variation of Pressure Sensitivity with Capsule Thickness

Difficulty was experienced in obtaining Harper Wyman 18 mm diameter capsules in anything other than the standard 0.127 mm diaphragm thickness. Because of this the variation of pressure sensitivity with diaphragm thickness was measured by thinning down standard capsules using an electropolishing technique.

The capsule to be thinned was prepared by brazing it to a capillary tube and ball sealing the top boss assembly. The capsule and capillary were fitted into the electro-polishing electrode assembly in the way shown in fig. 37. An electropolishing bath was made up using 95% glacial acetic acid and 5% perchloric acid and the electrode assembly and capsule were submerged beneath this mixture. Two 3 amp power supplies were connected to the electrodes in the manner shown in fig. 37.

The temperature of the electropolishing bath was monitored throughout the electropolishing process and maintained between 14 and 20 $^{\circ}$C by adding dry ice to the bath when required. Experience with the electrode assembly (fig. 37) showed that the current to the front electrode had to be set at 1.6 A and that to the rear electrode set at 2.6 A, otherwise a pitted surface finish was produced on the capsule, instead of the desired highly polished finish. The power supplies were set to give these currents, then were switched on simultaneously and switched off 20 seconds

later, to avoid overheating the bath. This was repeated
as many times as was necessary to remove the correct
amount of metal from the diaphragms (one 20 second burst
very approximately removed 0.002 mm of metal), the bath
being allowed to cool back to 14 $^\circ$C between electropolish-
ing cycles.

Several samples were prepared, each thinned to a different
extent up to a maximum of 20 electropolishing cycles.
The pressure-extension curves were then measured, after
which the capsules were set in "metset" resin and sectioned
down their centre lines. The section was carefully
polished and the thickness of the top and bottom diaphragms
was measured at each of the 7 positions shown in fig. 23
using a microscope with a calibrated filar eyepiece.
The mean of all 14 thickness measurements and the standard
deviation were calculated. The mean pressure sensitivity
of the capsules ($\bar{X}$) was obtained from the pressure
extension data by the calculation:-

$$\bar{X} = \frac{.889 \times 10^{-3}}{\Delta P} \qquad \dots \dots \dots (7.2)$$

where ΔP was the pressure change needed to extend the
capsule from .127 mm to 1.016 mm extension. This
calculation was used to avoid any complication caused
by variations in capsule starting pressures.

The variation of $\bar{X}$ with mean thickness for Harper Wyman
18 mm diameter, A.I.S.I. 302 capsules (see figs. 23 and 24)
is shown in fig. 38. The error bars in the mean thick-
ness direction were the standard deviations in the
thickness measurements for each particular capsule.
Measurements 4b and 5b were made using unthinned capsules.
Later a few ready made thin capsules, produced using the
standard press tools, became available. Point A on fig. 38
is that measured for a capsule with .107 mm thick diaph-
ragms and point B that measured for a capsule with .0762 mm

thick diaphragms. These thicknesses were the nominal
thickness of the sheet metal used to make the diaphragms.

7.8 Capsule Pressure-Load Performance

A 18 mm diameter Harper Wyman capsule was prepared by
bonding a 6BA threaded stud onto its top boss and
brazing a capillary tube onto the lower boss. The 6BA
stud was screwed into the D.T.I. on the capsule
extension measuring apparatus (as shown in fig. 19c)
and locked firmly into position. The capsule lower
boss was gripped very firmly by the jaws on the capsule
extension measuring apparatus. Thus the capsule was
firmly fixed into position, and positive and negative
loads could be applied to the top boss through the
D.T.I.

Positive loading was investigated by mounting the capsule
extension measuring equipment vertically as shown in
fig. 19b. The capsule was pressurized to give a certain
extension, then loads of up to 20N were applied to the top
of the D.T.I. and the pressure required to restore the
capsule to its original extension was recorded. This
was repeated for different values of capsule extension,
up to a maximum of 1.0 mm.

The extension measuring equipment was then inverted as
shown in fig. 19c and a load of 20N was added to the
weight pan. The capsule pressure was increased to
give a 1.0 mm extension, then the load was gradually
reduced and the pressure required to restore the
capsule extension to 1.0 mm recorded. This was repeated
for different values of capsule extension.

Fig. 39 shows the result of these measurements and it
will be noted that the pressure-load measurements all
lay in very straight, parallel lines. This indicated a

very stable capsule pressure effective area throughout
the entire load and pressure range. The pressure effect-
ive area measured along line A-B on fig. 39, was found
to be 0.992 x 10^{-4} sq. metres and the ratio of pressure
effective area to active area was 0.324.

7.9 Permanent Set of Capsules

An unused Harper Wyman A.I.S.I. 302 steel, 18 mm
diameter capsule was prepared by ball sealing the top
boss and brazing a capillary onto the bottom boss. The
capsule was clamped in the capsule extension measuring
apparatus (see fig. 19a), the D.T.I. zeroed and the
capsule pressurized to an extension of 0.4 mm. It was
left at this extension for approximately one minute,
then the pressure was reduced to zero and the residual
extension (called permanent set) showing on the D.T.I.
recorded after an interval of one minute. The pressure
was then increased to 138 kPa and the extension recorded
again.

The capsule was then taken to progressively higher
extensions and the zero pressure and 138 kPa extensions
recorded after each extension of the capsule. Because
these capsules were made with the diaphragms sprung
together slightly, permanent set was masked until it
became sufficiently large to exceed this prestress. It
was for this reason that 138 kPa extensions were measured
to check for hidden permanent set. Fig. 40 shows the
permanent set measurements and the change in 138 kPa
extension plotted against maximum extension for several
Harper Wyman A.I.S.I. 302 capsules.

Capsule number 7 (see fig. 40) was set in "metset" resin
and then sectioned down its centre line. Microhardness
readings were taken at different positions on the
diaphragms and were found to vary between H_V 340
and 383.

Several Harper Wyman 18 mm diameter capsules were made
with 0.127 mm thick 17-7 PH diaphragms. The diaphragms
were formed using annealed material and the finished
capsule assembly was later heat treated by maintaining
it at 760 $^{\circ}$C for 90 minutes, followed by 30 minutes at
room temperature then 90 minutes at 565 $^{\circ}$C. This process
precipitation hardened the diaphragms and the capsule
was tested as described above.

The heat treatment removed all capsule prestress, so
permanent set was not masked and the permanent set and
138 kPa extension readings increased in unison as the
capsules were taken to higher maximum extensions. It
was found that extension to 1 mm gave a permanent set
of between 0 and .06 mm for the samples tested. The
hysteresis of the capsules was checked over the extension
range 0 to 1 mm and found to be less than .005 mm (much
less than the standard capsule - see fig. 25).

7.10   Fatigue Life of Capsules

Part of the multi-purpose test rig was dedicated to the
pressure cycling of capsules. Referring to fig. 14,
nitrogen gas from a cylinder was regulated down to a
set pressure by pressure regulator R1. The nitrogen
flowed through shut off valve V2 to a 3 way A.C.
solenoid valve V10, which was operated by an electronic
control unit. V10 opened to allow the gas to flow to
4 capsules, connected to the test points (see fig. 14).
The capsules were then pressurized to the level set by
R1. After a period of time set by the control unit,
V10 changed over and allowed the gas pressurizing the
capsules to be exhausted to the atmosphere via V5, which
was left open. V3 was normally left shut. Thus as V10
alternated between its two positions, the capsules were
cycled between atmospheric pressure and a high pressure
set by R1. If desired V5 could be left shut and the
capsules cycled between the pressure set by R1 and a

lower pressure set by back-pressure regualtor R2. A
pressure switch was arranged to stop the rig from oper-
ating when the nitrogen cylinder ran out of gas.

Fig. 41 shows the control circuit which operated V10.
Waveform generator IC1 produced a square wave output
which could be varied between 0.6 Hz and 3 Hz by RV1.
The output of IC1 was buffered by IC2 which drove TR1.
This transistor switched the current passing through the
coil of RL1 on and off, and the contacts of RL1 controlled
the 240 V A.C. supply to solenoid valve V10. A resettable
counter was provided to count the number of cycles.

The 4 capsules to be tested were ball sealed and brazed
to a capillary tube. The pressure-extension curves
were measured and as these varied considerably, a
compromise setting for the cycling pressure was decided
upon, so that each of the 4 capsules would be cycled to
an extension somewhere in the desired range. The capsules
were bonded into a valve body (as in fig. 32) using
"metset" F.T. resin, so that they could be easily broken
from the valve body enabling it to be reused many times.
The inlet on the body was sealed and the rubber gasket
and cover plate were fitted to the back of the body.
A pressure switch set to operate at 20 kPa was screwed
into the valve body outlet.

The capillary tubes were connected to the test points
and the pressure switches plugged into the leak detector
unit (fig. 42). The cycling controller was switched
on and the capsules were cycled between atmospheric
pressure and the set pressure, until one had developed
a leak sufficient to operate the pressure switch. This
switched current to the gate of one of the C103YY
thyristors in the leak detector unit, turning it on.
When turned on the thyristor pulled the base of TR1 in
the control unit (fig. 41) to below the 0V level,
turning off the transistor and preventing the rig from

cycling any more. A L.E.D. on the leak detector unit
was illuminated to show which capsule had leaked. Even
if the pressure switch opened its contacts again, the
rig would not resume cycling, as the C103YY thyristor
would remain conducting until the control unit was
switched off and then on again. In this way, the rig
cycled the capsules until approximately 3 atmosphere cm^3
of gas had escaped from any one of them. .

In all 61 capsules were tested in this way, up to a
maximum of 100,000 cycles. Fig. 43 shows the number of
cycles at failure, plotted against the extension to which
the capsule was cycled, for the 20 capsules which failed.
It will be noted that no failures occurred at below
15,000 cycles and that most failures were due to cracking
of the weld securing the top boss to the top diaphragm.
Fig. 44 shows a section through such a cracked weld.

The cycling rig was also used to investigate the change
in the pressure-extension curve with cycle life. Four
standard Harper Wyman 18 mm diameter capsules were
connected to the cycling test points and given 50
689 kPa cycles to "season" the capsules. The pressure-
extension curves were measured and the capsules were then
given 20,000 cycles between 0 and 620 kPa (this gave
extensions between 1.062 mm and 1.030 mm). The pressure-
extension curves were remeasured and the capsules were
given another 80,000 cycles, after which the pressure-
extension curves were measured again.

It was found that on the whole there was a very small
increase in the extension at each point in the pressure-
extension curve, which became greater as the number of
cycles increased. The maximum increase observed in any
reading at 20,000 cycles was .008 mm ($\pm$ .005 mm) and the
maximum observed at 100,000 cycles was .015 mm ($\pm$ .005 mm).

7.11 Compliance of the Rubber Valve Seal

A valve plate (see fig. 18) was fitted onto the capsule
deflection measuring rig in the manner shown in fig. 45.
The valve plate was subjected to various central loads
up to 25N and the deflections measured. The results
of the experiment are shown in fig. 46. After the
test it was found that a compression set of 0.014 mm
remained. The stiffness of the test rig was also checked
with the valve plate removed and it was found that a
20N load cased a deflection of 0.01 mm.

7.12 Creep of Rubber Valve Seal

This was measured for the standard valve plate (fig. 18)
at different temperatures using the equipment shown in
fig. 47. The rig consisted of an accurate D.T.I.
(measuring to 0.0025 mm), which could be loaded and used
to measure the deflection of the valve plate under that
load. The valve plates were placed on the aluminium
'hot block' (see fig. 47) beneath the D.T.I.. This
'hot block' had a 14 W 10R resistor inserted through
its centre and a GM473 thermistor positioned inside
a boring just beneath the top surface. The circuit
shown in fig. 48 monitored the upper surface temperature
using the thermistor and varied the current through the
10R resistor to maintain a set temperature. An accurate
mercury in glass thermometer was also inserted down
a hole in the 'hot block' to enable its temperature to
be read. This equipment was found to be capable of
maintaining 'hot block' temperatures of up to 100 $^{\circ}$C
to an accuracy of $\pm\frac{1}{2}$ $^{\circ}$C.

To set up the equipment, the temperature controller
(fig. 48) was first of all adjusted to give the required
'hot block' temperature (for room temperature readings
the controller was completely turned off). An unused
valve plate was placed sealing lip downwards, at the

centre of the 'hot block' and the UNLOADED D.T.I.
positioned to measure the deflection of the centre of the
valve plate. Mineral wool insulation was then placed
over the top of the 'hot block' and valve plate to
prevent heat loss and the rig was then left for one
hour to allow the temperature to stabilize. The D.T.I.
was zeroed and loaded to 10N as quickly as possible.
One minute after loading the D.T.I. deflection reading
was noted and after that deflection readings were taken
at various times for a period of up to 1,000 hours.

Fig. 49 shows a plot of valve plate deflection against
log. time in hours for different valve plates at various
temperatures. It will be noted that after a settling
period of approximately one hour, the creep rate
stabilized to give a linear plot. The creep rates
obtained varied between 0.0085 mm per log. decade and
0.0055 mm per log. decade.

7.13   Thermal Expansion of Rubber Valve Seals

This was measured using the creep measuring apparatus
described in section 7.12. First the rate of expansion
of this test rig with increasing 'hot block' temperature
was measured. This was done by positioning the unloaded
D.T.I. (see fig. 47) so that it measured the expansion
of the centre of the 'hot block' and the top of the
block was insulated with a wad of mineral wool to prevent
heat loss. With the 'hot block' at room temperature,
the D.T.I. was zeroed and the temperature controller
was switched on to allow the 'hot block' to warm up to
a given temperature. The apparatus was left for one
hour for the temperature to stabilize, after which the
'hot block' temperature and D.T.I. readings were noted
down. This was repeated for several temperatures up to
100 $^{\circ}$C. Very consistent readings, corresponding to a
rig expansion of 0.000946 mm per degree C were obtained

(results plotted on fig. 50).

The rig was allowed to cool back to room temperature and a valve plate was fitted, sealing lip downwards, between the unloaded D.T.I. and the 'hot block'. The D.T.I. was positioned to measure the movement of the centre of the valve plate and the top of the valve plate and 'hot block' were insulated with a wad of mineral wool. The D.T.I. was zeroed and the temperature controller was switched on to allow the 'hot block' to warm up to a certain temperature. After being left to stabilize for one hour, the 'hot block' temperature and the D.T.I. reading were noted. This was repeated at various temperatures up to 100 $^\circ$C.

Three valve plates were tested in this way and the results are shown in fig. 50. The thickness of rubber seal (the dimension A in fig. 18) was measured on each of the three valve plates and the mean value was found to be 1.4 mm for sample 1, 1.37 mm for sample 2 and 1.12 mm for sample 3. From the readings plotted in fig. 50 it will be seen that the expansion of the valve seal and rig was 0.001480 mm per degree C. Subtracting the value of the rig expansion from this gives an expansion due to the rubber seal alone of 0.00053 mm per degree C. This corresponded to a linear expansion coefficient for the silicone rubber used to make the valve seal (General Electric Silicone Products type HH250P) of approximately 3.8×10^{-4} per degree C.

7.14 Long Term Testing of Thermal Systems

To enable the reliability of thermal systems to be checked under likely operating conditions, the test rig illustrated in fig. 51 was constructed. The rig had two standard oven burners, one of which had a gas flame that burned continuously and the other was arranged to have a flame that cycled on and off. For safety, the

continuously burning flame was sensed by a mercury F.F.D.,
which cut the gas flow back to a bypass rate if the
flame extinguished. The cycling burner had a pilot
fitted next to it, this pilot flame being sensed by
another mercury F.F.D. which interrupted the gas supply
to the cycling burner if the pilot extinguished. A
cyclic timer operated a solenoid valve which controlled
the gas flow to the cycling burner. This timer enabled
the flame on and flame off times to be varied independ-
ently between 5 and 200 seconds. When the solenoid valve
reinstated the gas flow to the cycling burner, the
pilot immediately relit the burner and no unburnt gas
was released to the atmosphere.

Five thermal systems were made up (as described in 7.3)
and checked by placing the capsule in the capsule
extension measuring apparatus (fig. 19a) and zeroing
the D.T.I.. The free end of the D.T.I. was then pushed
in under hard finger pressure, so that the capsule's
two diaphragms were forced back together. This gave
a measure of the capsule extension at ambient temperature
to an accuracy of $\pm$ .01 mm. The 5 thermal systems were
mounted so that the centres of their phials were in the
continuous burner flame on the test rig and the height
of the phials above the top of the burner was adjusted
to 25 mm. The running temperature of the phials was
checked by means of a thermocouple welded to one of them
and found to be approximately 700 $^{\circ}$C. The phials were
left in the flame and the capsule extension (with the
phial cool!) was checked every few weeks. At the end
of this life test, the results were as follows:-

Sample	Number of hours without failure	Duration of test-hours
1	335	(3603)
4	No failure	3603
6	No failure	4699
30	No failure	3239
35	No failure	3239

Samples 4, 6, 30 and 35 showed no significant change in
the capsule extension (and therefore fill pressure)
throughout the test.

Sample 1 showed signs of leaking when checked at 722 hours,
however testing was continued and the leak seemed to stop,
probably due to blockage by scale. The thermal system
was examined to establish the cause of the leak, but
none could be found and it is assumed that it was
probably due to a leak of the nicrobraz phial end seal.

The condition of all 5 A.I.S.I. 304 steel phials after
the end of testing was very good, with only some light
surface scaling. Fig. 52 shows the condition of the phial
on sample 35 after 2,700 hours continuous running. The
phial on sample 1 was sectioned after it had spent 3,603
hours in the flame and there was found to be no significant
metal wastage. The unaffected phial wall thickness was
maintained at 0.55 mm.

Four flame failure devices were made up and calibrated
as described in section 7.4. They were tested by
measuring the nitrogen flow rate through the valve at
0.75 mb pressure drop, with the phial heated to red heat
by a bunsen burner. The 4 devices were then mounted on

the long term test rig with the centre of the phials
placed in the cycling burner flame, 25 mm above the
burner top. The timer was set so that the burner was
on for $2\frac{1}{2}$ minutes and off for $2\frac{1}{2}$ minutes. The temperature
of the phials was checked using a thermocouple spot
welded to one of them and was found to vary between
75 ^{o}C and 700 ^{o}C when continuously cycling. These
F.F.D.'s were left on test and the flow performance of
the valve with the phial at red heat was rechecked every
few weeks. Any change in this performance indicated a
failure of the thermal system. At the end of this long
term test the opening temperature of each F.F.D. was
rechecked to see if it had deviated from the original
calibration. The results obtained for the four flame
failure devices tested were:-

Sample	Cycles without failure	Cycles in test	Set opening temp.	Opening temp. after test
13	36,798	(48,894)	----	----
25	30,240	(42.336)	----	----
32	No failure	38,532	299°C	319°C
34	No failure	38,532	308°C	306°C

The change in opening temperature for samples 32 and
34 were insignificant as the opening temperatures were
only accurate to $\pm$ 10 ^{o}C. All four valves were found
to be leak tight when checked after completion of the
test.

Valve 13 successfully completed 36,798 cycles without
performance change, but when rechecked at the end of

the test was found to have failed shut. When the phial
was sectioned it was found that the bore was very badly
eccentric giving an original wall thickness of only
.15 mm at one point. When examined after 48,894 cycles
the thinnest part of the wall had corroded through,
leaving a large split through which gas had escaped.
Metal wastage was found to be up to .15 mm on thinner
parts of the phial. Sample 13 successfully completed
30,240 cycles, but when examined at 42,336 cycles it
was found to have a reduced flow capacity indicating
a partial leak. The phial was sectioned and overall
metal wastage was found to be approximately 0.1 mm
leaving a minimum metal wall thickness of 0.26 mm
(the bore was slightly off centre). The capsule was
found to be leak tight and again the brazed phial end
seal was assumed to be the prime suspect for the cause
of the leak.

One of the mercury F.F.D.'s on the rig was taken off
after a total of 3388 hours in service. The phial was
sectioned and fig. 10 shows the condition of the
internal surface. The metallic deposits which can be
seen on fig. 10 were estimated to be up to 0.1 mm thick
in places.

CHAPTER 8

THE DESIGN AND PERFORMANCE OF GAS FILLED FLAME FAILURE

DEVICES

8.1 The Accuracy of Computer Performance predictions

Fig. 20, showing the pressure-extension performance of inconel X 750 capsule number 7, illustrates that some designs of capsule can make a close approach to having a linear pressure-extension performance. For such capsules the performance predictions made using a linear approximation to the pressure-extension performance were very accurate, as shown in fig. 29. The small discrepancies between measured and computed performances shown in fig. 29 were due to slight differences between the $\bar{X} = 2.28 \times 10^{-9}$ m/Pa linear approximation and the real pressure-extension curve and the fact that the measured value of S (the capsule volume factor - see section 7.6) was 0.49, rather than the 0.5 assumed by the computer program.

However capsule 7 was designed for high performance rather than ease of manufacture and mass produced capsules, such as those made for the mercury F.F.D. are not nearly so ideal in their behaviour. Fig. 21 illustrates the perfor- mance of capsule number 4, a Harper Wyman 18 mm diameter capsule, and the much higher non-linearity will be noted. The approximation to linearity ($\bar{X} = 1.8 \times 10^{-9}$ m/Pa) suggested for this capsule in fig. 21 was used to produce the computed performance prediction A in fig. 30. This prediction greatly overestimated the real performance of the thermal system (the crosses on fig. 30), therefore linear approximations cannot be used for capsules with non-linear behaviour such as that exhibited by capsule 4.

The reason for this performance overestimation is clear. The higher initial flexibility of a non-linear capsule

means that the pressure in the thermal system is lower
than that in an "equivalent" system with a linear capsule
at the same extension when the phials are at ambient
temperature. Thus the amount of fill gas in the non-linear
system is less than that in an equivalent linear system.
When the phial is heated, this smaller amount of gas has
to produce sufficient pressure to combat an ever increasing
capsule stiffness, thereby making the stroke of this thermal
system less than that of an equivalent linear system.

The actual pressure-extension measurements for capsule 4
(the crosses on fig. 21) were fed into the computer to
produce the performance prediction for thermal system 4,
which is shown as curve B in fig. 30. It will be observed
that this prediction was much closer to the measured
thermal system performance than that produced using the
linear approximation, but there was still a slight
performance overestimation. A computer performance
prediction made for thermal system 31 (this system also
used a Harper Wyman 18 mm capsule), using the pressure-
extension data shown in fig. 22, is illustrated in fig. 31.
Again the computed performance prediction slightly over-
estimated the real performance.

The reason for this discrepancy can be found in the high
hysteresis of the Harper Wyman capsules. Fig. 25 shows
hysteresis measurements made for such a capsule and explains
the origin of the performance reduction. For example, if
this capsule were made into a thermal system with a fill
pressure of 152 kPa gauge (a fairly typical fill pressure)
and the phial was heated taking the capsule to point B
on fig. 25, then as the phial subsequently cooled back to
ambient temperature, the capsule would follow the hysteresis
curve to point C. At point C the capsule extension would
be some 0.025 mm greater than it was when the thermal
system was first filled (this is a slight simplification
as it ignores the resulting small pressure reduction inside

the thermal system). From then on, as the phial is heated
and cooled, the capsule would follow the hysteresis loop
C-D-B-C and approximately 0.025 mm of stroke would be
permanently lost.

Therefore it can be seen that the computer predictions
are very accurate indeed, the only source of error being
a fairly small one due to capsule hysteresis. If need be
the hysteresis could be allowed for, providing some idea
of the expected thermal system performance was known.
The capsule hysteresis could then be measured over the
expected working range and the pressure-extension data
used to produce the computer prediction adjusted accordingly.
If computer predictions are made using a linear approxim-
ation to the true capsule pressure-extension curve, then
optimistic performance predictions must be expected,
unless the capsule used had a very linear performance.

8.2 The Computed Design Curves

To help a designer select the optimum thermal system
design, computer predictions were made to show how the
performance would vary with different design parameters.
In this case, the capsule performance was assumed to be
linear, as the introduction of non-linearity would tend
to confuse the issues. Therefore these computed pre-
dictions represent the maximum achievable performance,
which the designer should aim for, remembering that any
non-linearity would reduce the performance.

For these design curves a realistic range of variation
was estimated for each design parameter.

a) Phial Volume V_p

Size limitations restrict the variation of V_p to the
range 0 to 1,000 mm^3, although it would be advatageous
to keep the volume to less than 500 mm^3 to enable the

phial to replace a standard mercury F.F.D. phial.

b) Dead Volume U

The experimental thermal systems made during this work had a typical dead volume of 60 mm^3. A realistic range of dead volume for this type of thermal system would be from 0 to 150 mm^3.

c) Capsule Diameter and Pressure Sensitivity

Capsules are generally made in traditional standard sizes, nominally ⅝, ¾, ⅞, 1 and 1½ inch, although the active diameter is normally slightly less than this. Therefore this study has been restricted to diameters of 15 to 35 mm. Particular emphasis is placed on the study of 18 mm diameter capsules as this was the size of a Harper Wyman capsule which seemed particularly suitable for development for gas filled F.F.D. use.

The pressure sensitivity is related to the diaphragm thickness and diameter and this relationship is discussed in section 8.3. However for the types of capsule likely to be suitable for these devices the pressure sensitivity would lie in the range from 10^{-9} to 5×10^{-9} m/Pa.

d) Fill Pressure P_f

The flexibility of the capsule and the maximum safe deflection put a limit on the maximum fill pressure, if the deflection limit is not to be exceeded during operation. For the thermal systems studied here, the fill pressures would be in the range 0 to 350 kPa absolute.

Figs. 53 to 57 show how the stroke or valve lift produced by gas filled thermal systems is affected by changes in the design parameters. To summarize it will be seen that thermal system performance increases as:-

a) Capsule diameter decreases

b) Phial volume increases

c) Fill pressure increases

d) Dead volume decreases

e) Starting pressure increases

Increasing the fill pressure to improve performance must be done carefully so as not to cause yielding of the capsule. Raising the starting pressure, for instance by restraining the capsule with springs, will give a useful increase in performance. This can be a valuable way to increase F.F.D. performance and is descussed fully in section 8.5.

8.3   Capsule Design and Performance

The capsule is the key component in the thermal system and in order to be suitable for a mass produced gas filled F.F.D., it must satisfy the following requirements:-

a) Have a high pressure sensitivity, with a reasonably linear performance over the range of operation.

b) Be cheap to manufacture

c) Have stable, elastic properties

d) Have a low dead volume in the relaxed state

e) Be resistant to corrosion

The 15 mm and 18 mm diameter capsules used by Harper Wyman for their mercury F.F.D. production were evaluated for use in a gas filled F.F.D. design. The resistance welded A.I.S.I. 302 stainless steel construction of these capsules made them relatively cheap to manufacture and endowed them with high corrosion resistance. Fig. 24 shows that these capsules also nested extremely well giving a low dead volume, approximately 25 mm^3 in the 18 mm diameter design.

The first choice to be made in capsule selection is that of capsule diameter. As fig. 53 shows, thermal system perfor-mance is reduced as capsule diameter increases, therefore

the capsule diameter chosen ought to be small. However
with diaphragms of 15 mm diameter or less, the number and
depth of corrigations which can be produced is restricted
and the top and bottom bosses start to occupy a large
proportion of the diaphragm surface, resulting in an
unsatisfactory capsule design. Therefore it was decided
that the Harper Wyman 18 mm diameter capsule (figs. 23 and
24) offered most scope for development.

These capsules in their existing form had a mean pressure
sensitivity which varied between 1.5 and 2.1 m/Pa (see
section 7.2). This was fairly low and, as fig. 53 shows,
a good performance gain can be expected if the capsule
pressure sensitivity is increased. This is also true for
non-linear capsules, as reference to figs. 30 and 31 will
show that a more flexible capsule (fig. 31) gave approxi-
mately 0.06 mm extra stroke at 700 $^\circ$C to one of two
otherwise identical thermal systems.

The work of Wildhack et al (59) with N.B.S. type 1 diaphragms,
has indicated the following empirical relationship between
diaphragm pressure sensitivity and diaphragm thickness and
diameter:-

$$\frac{EX}{(1 - \nu^2) D} = K\left(\frac{t \times 10^3}{D}\right)^{-\beta} \qquad \dots\dots\ (8.1)$$

where X is the mean pressure sensitivity (m/Pa), D is the
diameter (mm), ν is Poisson's ratio, E is the elastic
modulus of the diaphragm material (Pa), t the diaphragm
thickness (mm), and β and K are constants. Although the
equation was derived for a particular family of diaphragms,
Newell (42) suggests that it could be applied to other
diaphragm shapes with β ranging from 1 to 2, with a typical
value of 1.5 (N.B.S. 1, β = 1.52 - see reference 59). In
the experiment described in section 7.7, Harper Wyman
18 mm diameter capsules were thinned and $\bar{X}$, the mean

pressure sensitivity, was compared to the diaphragm thickness. The results shown in fig. 38 demonstrate that the value of β for this type of capsule lies well within the range 1 to 2, with a most probable value of 1.5. Thus equation 8.1 with β set to 1.5 and K set to 415, can be used to predict the variation of $\bar{X}$ with thickness. The solid line on fig. 38 illustrates the nature of this variation for the 18 mm Harper Wyman capsule.

Due to the low pressure sensitivity of the standard 0.127 mm thick capsule, it is suggested that for gas filled devices the capsule thickness be reduced to 0.1 mm. From fig. 38 it will be seen that this would increase $\bar{X}$ to about 2.6×10^{-9} m/Pa. The wide spread of capsule pressure sensitivities has already been noted and if this range scales in the same way as $\dot{\bar{X}}$ when the diaphragm thickness is reduced to 0.1 mm, then a sensitivity range of 2.1 to 2.9×10^{-9} m/Pa would be expected. These large pressure sensitivity variations are unavoidable in a mass produced capsule, as they are due to variations in the original thickness of the sheet metal used to make the diaphragms and variable thinning due to stretching during the pressing process (the unthinned samples 4b and 5b shown in fig. 38 illustrate the amount of thickness variation found in individual capsules). Also the corrugation shapes will tend to vary between capsules, due to the differing amounts of spring-back after pressing (due to the variations in the yield point of the strip used). However the capsule used to make F.F.D. number 31 had an $\bar{X}$ (measured using equation 7.2) of approximately 2.2×10^{-9} m/Pa and as this F.F.D had an acceptable performance (see section 8.5), then most capsules made using 0.1 mm thick diaphragms would have sufficient pressure sensitivity for a gas filled F.F.D.. Reduction of the diaphragm thickness to much less than 0.1 mm would not be very practical for mass production, as difficulty would be encountered in fabrication. In fact .075 mm is generally recognised to be the absolute minimum

diaphragm thickness for practical capsules.

Reducing the diaphragm thickness may also help improve
capsule linearity. Wildhack et al (60, 61) in their
research with N.B.S. type 1 diaphragms found that a
maximum linearity (for deflections up to 4% of diaphragm
diameter) was achieved when the ratio of diaphragm
thickness to diameter was 2×10^{-3}. Thicker diaphragms
had a decreasing pressure sensitivity with increasing
extension and thinner diaphragms tended to have an in-
creasing pressure sensitivity with increasing extension
(although for extensions greater than 4% of diaphragm
diameter, the pressure sensitivity started to decrease
rapidly with extension). Reducing the thickness of the
Harper Wyman 18 mm diameter capsule to 0.1 mm would change
the thickness to diameter ratio from 7×10^{-3} to 5.5×10^{-3}.
Increasing the corrugation depth also increases capsule
linearity (59, 42, 61) and the designer should attempt
to make these as deep as the pressing process will allow.
The comparison of the leading dimensions of the very linear
inconel X 750 capsules made by Pressure Sensors Ltd.
(pressure-extension curve shown in fig. 20) and the much
more non-linear Harper Wyman capsule (see fig. 21 for
pressure-extension curve) will help amplify the points
made above.

CAPSULE TYPE	DIA. (D)	THICKNESS (t)	t/D x10^3	NUMBER OF CORRUGS.	CORRUG. DEPTH	CORRUG. LENGTH
H.W.	18mm	.127mm	7	4½	.22mm	1.7mm
P.S.	18mm	.075mm	4.2	2½	.32mm	2.1mm

More sophisticated design studies can be made using a
finite element stress analysis technique, for which both

the Battelle Memorial Institute (62) and Baxter (63) have
developed computer programs. However, in view of the spread
of capsule characteristics, their predictions will be no
more accurate than those produced by simpler methods.
The advantage of finite element analysis is in examining
radical new diaphragm designs where little practical
experience exists, or in the design of precision capsules.

Finally the diaphragm material must be chosen and in
doing this two points must be borne in mind, the corrosion
resistance and the maximum deflection required from the
capsule. Obviously with diaphragms of only 0.1 mm
thickness which are meant to last for at least 10 years,
in what could well be a warm damp environment, any
corrosion would be totally unacceptable. Therefore the
chosen material must be highly corrosion resistant.

The maximum strain in the material of a diaphragm which
is subjected to a deflection, is approximately proportional
to the deflection expressed as a percentage of the diaphragm
diameter.(61). The maximum stress in the material will
be given by this maximum strain multiplied by its modulus
and if this maximum stress exceeds the yield stress, then
the capsule would suffer a "permanent set" (permanent
deflection of the capsule). This is clearly undesirable
and the capsule material and working range must be chosen
to avoid this. A measure of the merit of a particular
diaphragm material is therfore the ratio of the yield
stress to the modulus (61) and the best materials would
have a high strength/modulus ratio. Table 7 summarizes
these properties for some commonly used diaphragm materials.
The copper alloys listed in table 7, although having very
good properties, can be ruled out for a mass produced
capsule as they cannot normally be resistance welded.
Soldering and brazing techniques, although very useful on
a small scale, are diffucult to apply to capsule mass
production. The most commonly used material for mass

produced capsules is A.I.S.I. 302 stainless steel (or
similar austenitic steel). This material is relatively
cheap and readily available in diaphragm quality strip,
however it cannot be hardened except by cold work. Thus
material must be chosen which is soft enough to form
into diaphragms, but which when formed, will be hard
enough to confer reasonable spring properties to the
diaphragm. It is for this reason that the Harper Wyman
capsules are made from "½ hard" A.I.S.I. 302 strip, with
a specified hardness range of H_v 220 to 290 and finished
diaphragms would be work hardened (see section 7.9), to
give a yield stress of about 800 MPa. Fig. 40 illustrates
the results of permanent set tests on Harper Wyman 18 mm
diameter capsules (see section 7.9). There was a signif-
icant amount of pre-stress in these capsules (caused by
the top and bottom diaphragm being sprung against each
other) and, as a previously unused capsule was taken to
progressively higher maximum extensions, this pre-stress
was reduced by yielding as indicated by the rise in the
138 kPa deflection reading. It will be noticed that as
the maximum extension was taken beyond approximately
1.1 mm the yielding was sufficient to produce a permanent
set, which increased rapidly with progressively larger
extensions.

However this does not present too many problems, because
if the capsule was initially extended to say 1.0 mm,
then subsequent extensions below this maximum would cause
very little extra yielding and the capsule performance
would be reasonably stable. This gives rise to the
process called "seasoning" (59), where capsules are
pressurized to a deflection just beyond their working
range so as to stabilize the pressure-extension character-
istics. For the Harper Wyman 18 mm diameter capsules
tested, it was found that one pressurization was sufficient
to give good enough subsequent stability for gas filled
F.F.D. purposes. As all capsules are pressure tested
for leaks during the manufacturing process, the need for

seasoning should cause no problems. Taking the capsule
extension to beyond 1.1 mm however, would have a detri-
mental effect on it, as the large amount of permanent set
would increase the capsule dead volume.

Table 7 indicates that 17-7 PH stainless steel would be
a good choice of material for diaphragms. This material
has all the advantages of 302 stainless steel, but can
be precipitation hardened, enabling the diaphragms to
be pressed from soft material and then hardened later.
Some capsules with 0.127 mm thick diaphragms in this
material were tested (section 7.9) and found to have
good performance. When hardened, the typical permanent
set after extension to 1.0 mm was between 0 and 0.06 mm
(due to the heat treatment, there was no pre-stress to
mask the permanent set), whereas the 302 steel capsules
had a change in 128 kPa extension (the hidden permanent
set) of around 0.1 mm. Also the 17-7 PH capsules were
found to have a much lower hysteresis (< .005 mm) than
the 302 capsules (~.03 mm).

These tests indicated that 17-7 PH was indeed a good
capsule material (Trainer (62), recommends its use for
bellows). The fact that softer material can be used
for pressing the diaphragms, should enable a better
diaphragm shape with deeper corrugations to be made.

8.4 Capsule Fatigue Life

When fitted to cooker ovens, a gas filled F.F.D. capsule
would probably experience some 3,000 cycles in a 10 year
life (29). This cycling has caused fatigue failures in
mercury flame failure devices (see table 3 and 4) and
there is a similar danger for the gas filled device.
The work to determine how the fatigue life of standard
Harper Wyman 18 mm diameter capsules was affected by
different amplitudes of cyclic stressing is described
in section 7.10. The results of these tests, in which

capsules were cycled from a zero extension, are shown in
fig. 43. It will be noted that out of the 61 capsules
tested, none failed at below 15,000 cycles. Between
15,000 and 100,000 cycles there were 20 failures, all
but one occurring when the capsules were extended to
beyond 1 mm. The one failure which occurred at less than
this cyclic extension was due to an edge weld leak.

Reference to fig. 43 shows that in the interval between
maximum cyclic extensions of   1.118 mm and 1.168 mm
there were a total of 8 failures and one "run out".
Statistical analysis of the failures, assuming a log -
normal distribution, enabled the number of cycles for
a given percentage survival to be estimated with 95%
confidence. The 95% survival cycle life was estimated
to be 7,100 cycles and the 99% survival cycle life was
3,900 cycles. It is suggested that, because of the
closeness of the 99% survival life to the expected
working life, that capsules never be taken beyond 1.1 mm
in cycling. For design purposes it would be prudent to
assume a 1.0 mm maximum extension cycle as the limit,
in order to give an additional safety factor.

The mode of failure was also very interesting. Classic-
ally capsule fatigue failures occur at the outermost
corrugation (63), as this is normally the point of maxi-
mum cyclic stress. However by far the most common cause
of capsule failure encountered (14 capsules failed in this
way) was cracking of the top boss weld (see fig. 43).
Fig. 44 shows a section through a cracked top boss weld
and when viewed in conjunction with the complete capsule
section shown in fig. 24, it will be appreciated that
this weld is acting as a stress raiser, leading to early
failure. Normally the stress raising effects of welds
can be reduced by producing a weld with a 'fillet',
however as economic factors dictate the use of a projection
weld, it is difficult to see how this could be done. An
improvement might be to reduce the top boss diameter,

as due to the curvature of the extended diaphragm, this
would reduce the stresses at the weld. Only one bottom
boss weld failure was noted, believed to be due to the
assymetric capsule design producing lower stresses on
this weld.

Unfortunately no tests were conducted on 0.1 mm thick
capsules because of lack of samples. However one 0.1 mm
thick prototype was tested up to 100,000 cycles (between
0 and 1.002 mm extensions) without failure, indicating
that a well made thin capsule should have a reasonable
fatigue life.

When working as part of a pressurized thermal system
the capsule would not be cycled between zero extension
and a maximum value, but between some positive extension
and a maximum extension. This is especially so in designs
of F.F.D. in which the valve plate is attached to the
top of the capsule, where the capsule is prevented from
relaxing to its rest state and therefore the actual capsule
movement is much reduced. The maximum capsule extension
before occurrence of permanent set (see section 8.3) and
the fatigue life data must therefore be taken in comb-
ination to produce guidelines indicating the working
limits of a particular capsule, under these differing
conditions.

The capsule must never be taken beyond the point where
serious permanent set appears, i.e. the following
condition must be adhered to:-

$$b + c < b_{max} \qquad \dots\dots\dots (8.2)$$

where b is the static deflection (at the fill pressure),
c is the amplitude of the cyclic deflection and
b_{max} is the maximum extension before permanent set occurs.

When assessing the affect of mean stress on fatigue life,

the Goodman law (64) is commonly used:-

$$\sigma_{an} = \sigma_n \left(1 - \frac{\sigma_m}{\sigma_u} \right) \qquad \dots\dots\dots (8.3)$$

where σ_n is the fatigue strength for a given cycle life,
σ_{an} is the stress amplitude for the same cycle life when
a mean stress σ_m is also applied and σ_u is the ultimate
tensile strength of the material. For a capsule, the
material cannot be taken to its ultimate tensile strength
as permanent set would be encountered, therefore it is
suggested that σ_u is replaced by the yield stress (σ_u is
approximately 1.25 x the yield stress for ½ hard A.I.S.I.
302 steel). As mentioned before the stresses in the
capsule are approximately proportional to the capsule
extension, therefore the stresses in equation 8.3 can be
replaced by deflections to give:-

$$c \leq \frac{c_{max} \, b_{max}}{b_{max} - \frac{1}{2}c_{max}} \left(1 - \frac{b_m}{b_{max}} \right) \qquad \dots\dots\dots (8.4)$$

where $b_m = b + \frac{c}{2}$ $\qquad \dots\dots\dots (8.5)$

where c_{max} is the maximum cyclic deflection for a given
percentage survival cycle life when cycling from zero
extension, c is the maximum cyclic deflection for the
same cycle life when a static deflection b is also applied
and b_{max} is the maximum extension available without
permanent set. Providing c is kept to less than, or
equal to the function in equation 8.4, the capsule fatigue
life will be greater than, or equal to that measured for
c_{max}. In fact this guideline is very conservative as,
due to the use of the yield stress, the allowable values
of c will be less than those which would be predicted
by the Goodman law.

Therefore, providing the capsule's operating extensions
satisfy the conditions shown in equations 8.2 and 8.4,
the fatigue life will be better than that measured for
zero to maximum extension cycling. For the 18 mm diameter
Harper Wyman capsules tested, b_{max} was 1.1 mm (see fig. 40)
and the value suggested earlier for c_{max} was 1.0 mm.
Therefore the operating conditions of these capsules must
satisfy both of the following relationships.

$$b + c < 1.1 \qquad \text{....... (8.6)}$$

$$c < 1.83 - \frac{b_m}{0.6} \qquad \text{....... (8.7)}$$

In section 7.10 the "drift", or change in the pressure-
extension performance, was measured for the standard
18 mm diameter Harper Wyman capsule over 100,000 cycles.
In the test four capsules were cycled between zero
extension and extensions between 1.033 and 1.062 mm,
which it will be noted was just beyond the suggested
limits for these capsules. The changes in performance
measured were very small indeed, suggesting that
providing these capsules are kept within the limits laid
out in equations 8.6 and 8.7, they will perform reliably
and repeatably for more than 30 times the anticipated
cycle life.

8.5   The Gas Filled F.F.D.

Most domestic cooker ovens on the British market have a
maximum consumption of 0.283 cubic metres (10 cu. ft.)
per hour of natural gas. Gas flow ratings for valves
were traditionally specified at 0.75 mb (0.3" w.c.)
pressure differential. However the recent British Standard
(13) has increased this to 1.0 mb differential. The
0.75 mb flow ratings are discussed here, but these are
easily converted to 1.0 mb ratings using the following
equation developed from equation 7.1:-

$$F_1 = F_2 \sqrt{\frac{\Delta P_1}{\Delta P_2}} \qquad \ldots\ldots\ldots (8.8)$$

where F_1 and F_2 are the flow rates at ΔP_1 and ΔP_2 pressure differential respectively. Therefore 0.75 mb ratings are converted to 1.0 mb ratings using:-

$$F_{1.0} = F_{0.75} \times 1.15 \qquad \ldots\ldots\ldots (8.9)$$

The 0.75 mb pressure drop will be divided between the valve body and the valve seat (see section 7.1). Fig. 16 shows the pressure drop for a valve body with ¼" B.S.P. connections to be 0.09 mb at this flow rate. However the same valve body is also manufactured with smaller connections, therefore, including some safety factor, a pressure drop of 0.25 mb can be assumed for the valve body itself. When designing valve bodies, the pressure drop due to the body must be kept as small as possible, by making the gas ways as large as can be accomodated and by attempting to reduce all factors restricting the gas flow.

Fig. 17 shows the measured flow rate of natural gas past the standard 25 mm diameter valve plate and seat at different valve lifts (see section 7.1). Allowing 0.25 mb pressure drop for the body, leaves 0.5 mb pressure drop across the valve. At this pressure a valve lift of 0.132 mm is required to give a gas flow of 0.283 cubic metres per hour (see fig. 17). If a different valve plate diameter is desired, for instance to produce a higher flow rated F.F.D., the required valve lift would be:-

$$L = L_{25} \times \frac{25}{D} \qquad \ldots\ldots\ldots (8.10)$$

where L_{25} is the valve lift obtained from fig. 17, and D

is the diameter in mm of the valve plate. It will be
noted that this design data only applies to the standard
valve plate and seat as shown in fig. 18, but as this
design has proved entirely successful there seems no
reason to change it except for altering the diameter.

Appliances are sometimes fuelled by other types of gas
such as L.P.G. and to a decreasing extent town gas. For
these different gas "families", the flow rate through
the valve at the same pressure drop can be obtained by
modifying equation 7.1:-

$$F = F_N \sqrt{\frac{\rho_N}{\rho}} \qquad \qquad \dots\dots\dots (8.11)$$

where F is the flow rate of gas with density ρ, F_N is
the flow rate of natural gas and ρ_N is the density of
natural gas. Table 8 gives densities of various fuel
gases.

However this is not the complete picture as more or less
gas may be required due to the different calorific value
of the gases. This introduces the concept of the Wobbe
index, W, of fuel gases (10).

$$W = \frac{C_g}{\sqrt{d}} \qquad \qquad \dots\dots\dots (8.12)$$

where C_g is the calorific value of the gas and d its
relative density. Therefore the heat throughput which
will be passed by the F.F.D. when using a different gas
is given by:-

$$H = \frac{W}{W_N} \cdot H_N \qquad \qquad \dots\dots\dots (8.13)$$

where H_N is the heat throughput using natural gas and
W and W_N are the Wobbe indices of the new gas and natural
gas. Table 8 lists some Wobbe indices.

A thermal system must therefore be capable of producing
at least 0.132 mm value lift (for a 25 mm valve) to be
suitable for cooker ovens. Perusal of the design curves
(figs. 53 to 57) showing the strokes produced by various
thermal system designs would suggest that a gas filled
thermal system ought to be able to produce sufficient
valve lift. Indeed, this has been borne out by experi-
ment and fig. 33 shows the flow performance of F.F.D.
number 31 (with a 25 mm diameter valve plate), which was
set to open at 325 $^{\circ}$C. This valve was capable of passing
approximately 0.4 cubic metres of gas per hour at 0.75 mb
pressure drop, when the phial was heated to 700 $^{\circ}$C -
a very adequate performance.

The chosen F.F.D. opening temperature (T_s) determines
the flow performance of the device. The opening temper-
ature selected must be sufficiently high for the valve
to shut within the time shown in table 5 when the maximum
ambient temperature is encountered. Fig. 35 shows the
cooling rate of a gas filled F.F.D. phial in an oven at
maximum temperature and it will be noted that in the
90 seconds closing time allowed, the phial had cooled
to 215 $^{\circ}$C. Thus allowing for some safety factor, the
opening temperature of a F.F.D. ought to be in the range
275 $^{\circ}$C to 300 $^{\circ}$C, although each appliance application
must be individually checked. It is clear from the nature
of the thermal system performance curves (e.g. fig. 31)
that the lower the opening temperature, the greater the
flow performance. Therefore for applications where low
ambient temperatures are encountered, the opening
temperatures should be reduced, perhaps down to 200 $^{\circ}$C
(see the room temperature cooling curves on fig. 25).

F.F.D. opening times must also be within that specified
in table 5 (90 seconds for domestic ovens), when heated
by the small bypass flame on the main burner (see section

3.2.1), or a pilot (see section 3.2.2) and usually the
main burner bypass flame causes most problems. However,
experience with gas filled F.F.D. phials has shown that
providing they are positioned correctly, they will be
heated by a bypass flame to 300 $^{\circ}$C in approximately
10 seconds and reach a stable temperature of around
500 $^{\circ}$C after one minute. Thus opening times should
present no problems.

The 500 $^{\circ}$C running temperature in a bypass flame would
give a 0.75 mb flow rating of 0.23 cubic metres per hour
for experimental F.F.D. 31 (see fig. 33), but dropping
the opening temperature from 325 $^{\circ}$C to 275 $^{\circ}$C would give
a rating in the region of 0.28 cubic metres per hour at
500 $^{\circ}$C. However once the F.F.D. opened partially, the
positive feedback effect of the increased flame size
would open the F.F.D. fully. Normal phial temperatures
encountered in burner flames once the F.F.D. has opened
are in the region of 600 $^{\circ}$C to 700 $^{\circ}$C. Pilots present
no problem, as even a very small flame can be arranged
to heat a phial to 700 $^{\circ}$C.

The experimental F.F.D.'s produced during the present
research (e.g. F.F.D. 31, fig. 33) proved that a gas
filled F.F.D. can have the required performance for a
domestic oven application. Therefore it is envisaged
that a production version of the gas filled F.F.D. would
not be very different from the experimental devices made
for this work. The choice of a 500 mm^3 phial is
recommended for a production version, as this is not
over large and gives an adequate performance. If the
design requires a different sized phial, fig. 54 gives
some indication of the change in thermal system perfor-
mance to be expected. As was stated in section 8.3, a
0.1 mm thick capsule if recommended for a production
device, rather than the 0.127 mm thick capsule used to
make F.F.D. 31. However the capsule used in F.F.D. 31
was selected for high pressure sensitivity and represents

the expected minimum flexibility of 0.1 mm capsules.
Therefore the performance of F.F.D. 31 (fig. 33) represents
the minimum to be expected from flame failure devices
with 0.1 mm capsules. The effect of capsule pressure
sensitivity on F.F.D. performance can be gauged from the
design curves.

The fill pressure chosen should be as high as possible
to give the maximum performance (fig. 55), but should
not take the capsule beyond the working range specified
in sections 8.3 and 8.4. Here the 1,000 $^{\circ}$C phial
temperature test required by BS 6047 must be taken into
account, however this should present no problem, due to
the constantly reducing gradient of the phial temperature-
stroke curve. In service no temperature greater than
850 $^{\circ}$C would be encountered, even with a maximum aeration
gas flame. Designs should also aim at minimising the
dead volume, by using a well nested capsule and a very
small bore capillary tube.

Finally there is a choice of several modes of construction.
The valve could be actuated via levers, although expensive,
this would be useful where a high flow performance was
required. The main choice lies between the attachment
of the valve to the top of the capsule, as in fig. 32,
or the use of a spring to hold a separate valve plate
on its seating, as in the standard mercury F.F.D. shown
in fig. 5. Both methods have advantages and disadvantages,
some of which are listed below:

Attached valve plate - advantages

    a) Does not require a spring

    b) The valve plate does not move relative to the
valve seat, so the rubber seal will "bed in" properly

    c) Easier to assemble in production, as the valve
plate simply has to be screwed onto a fixed stud.

Attached valve plate - disadvantages

a) The stud fitted to top of capsule must be perpendicular and concentric to the capsule

b) Possible extra stress on the weld fixing the stud to the top diaphragm, lowering the fatigue life

Separate valve plate - advantages

a) Useful performance increase due to the spring pressure

b) Construction similar to the mercury F.F.D.

c) Tolerances on the top boss fixing much wider than with attached valve plate designs

Separate valve plate - disadvantages

a) Extra cost of spring

b) The valve plate will tend to rotate and not bed into the seat so well

c) There is a possibility of wear between top boss and valve plate adjustment screw. This would affect the calibrated opening temperature of the F.F.D.

Both methods are practical, and it is up to the manufacturer to decide which method suits the prevailing circumstances best.

The chance of increasing performance by restraining the capsule with a spring force was noted earlier and the method of construction with the valve plate held down by a spring clearly lends itself to this. The pressure effective area of a Harper Wyman 18 mm diameter capsule has been measured at 0.992×10^{-4} square metres (see section 7.8) and this can be used to convert the spring force to a starting pressure (P_s). Fig. 57 illustrates how increasing P_s improves thermal system performance.

A fairly stiff spring of 10N force would give a P_s of 101 kPa and for F.F.D. 31, computer predictions indicated that this would improve the capsule stroke between 300 $^{\circ}$C and 700 $^{\circ}$C from 0.196 to 0.241 mm, a very worthwhile performance improvement. However increasing spring forces too much could cause problems due to valve seal creep (see section 8.7). If ways could be found to incorporate high spring loads, without also causing creep problems, then as fig. 39 shows, capsules can withstand loads of at least 20N without change in the pressure effective area. If a 20N load were applied to F.F.D. 31, the 300 $^{\circ}$C to 700 $^{\circ}$C stroke would be improved to 0.28 mm. This would be equivalent to a flow rate of approximately 0.5 cubic metres per hour at 700 $^{\circ}$C (when T_s = 300 $^{\circ}$C) and a full flow of 0.28 cubic metres per hour would be achieved at 450 $^{\circ}$C (compare to fig. 33). The springs chosen to load the capsules must have a low rate, as an increase in loading with capsule stroke would reduce the expected performance gain. With this proviso, it will be seen that a spring can be used to produce a valuable performance increase in a gas filled F.F.D. design.

8.6   The Variation of F.F.D. Performance with Ambient Conditions

As might be expected with a gas filled device, variations in ambient temperature and pressure will considerably affect the opening temperature of the valve. Program var.basic (see section 5.4.2) was written to investigate the variation of opening temperature (T_s) with ambient conditions and fig. 58 shows the results for F.F.D. 31 with no temperature compensation. The rectangle A-B-C-D on fig. 58 indicates the range of conditions which might be encountered in the U.K. and it will be seen that under extreme circumstances, the opening temperature is likely to drop from 325 $^{\circ}$C to 250 $^{\circ}$C.

This amount of reduction in the opening temperature cannot be tolerated in a practical F.F.D., however temperature compensation is easily achieved, since most rubbers have very high thermal expansion coefficients - typically 2.5 to 4 x 10^{-4} per degree C for silicone rubber (65). The high expansion of the rubber seal can be used to compensate for ambient temperature effects. The standard silicone rubber valve seal was found to expand by 5.3 x 10^{-4} mm per degree C (see section 7.13), equivalent to a linear expansion coefficient of approximately 3.8 x 10^{-4} per degree C. Fig. 59 illustrates the variation of T_s with ambient conditions for F.F.D. 31 with a temperature compensation provided by a valve seal expansion of 7 x 10^{-4} mm per degree C. It will be seen that this was the ideal amount of compensation for this particular F.F.D.. Under the most extreme U.K. conditions, the opening temperature would only fall from 325 $^{\circ}$C to about 300 $^{\circ}$C, which would be of no consequence under normal operating conditions. If sold to other countries, the F.F.D. may well be used at altitude and fig. 59 indicates the reductions in atmospheric pressure encountered at different altitudes.

To obtain the correct temperature compensation the thickness of the valve seal (dimensions A on fig. 18) would have to be changed. For F.F.D. 31 the thickness would need to be increased to 1.32 mm.

8.7 The Anticipated Life and Reliability of the Gas Filled F.F.D.

The long term tests (section 7.12) indicated that the life of a well made gas filled F.F.D. could be very long indeed. Four samples survived for longer than 3,200 hours in a continuous flame and four samples exceeded 30,000 cycles on a cycling burner. The three failures, as was explained in 7.14, were due to the shortcomings in the construction of the experimental F.F.D.s.

One of the factors limiting F.F.D. life would seem to be
phial metal wastage, due to oxidation and/or carburization
by the gas flame. However for the samples tested on a
continuous gas flame, the amount of metal wastage observed
after 3,600 hours at 700 $^{\circ}$C was insignificant. Therefore
the life of a 0.5 mm thick A.I.S.I. 304 phial under these
conditions is expected to be very long, probably much
greater than 10,000 hours. Cycling conditions, as would
be expected, produced much accelerated phial wastage.
Approximately 0.1 mm of metal was lost after 40,000 2½
minute hot, 2½ minute cold cycles between 700 $^{\circ}$C and
75 $^{\circ}$C. Thus a 0.5 mm thick phial would certainly outlast
100,000 such cycles. Domestic oven operation would lie
between these two extremes, with approximately 3,000
hot cycles in 10 years, of average duration between
perhaps one and two hours. However the indications are
that a 0.4 or 0.5 mm thick A.I.S.I. 304 phial would
easily outlast this life. The 6,000 cycle BS 6047 test
(see section 5.1) would clearly present no problems for
a well made gas filled F.F.D..

No failures in the life tests could be attributed to
capsule fatigue and providing the capsule stressing guide-
lines in sections 8.3 and 8.4 were adhered to, domestic
oven service should present no problems. One worry was
that the low partial pressure of oxygen encountered in
a thermal system might cause fretting of the capsule,
however no sign of this was noticed on the samples which
were subjected to burner cycling (see section 7.14).

One important requirement of BS 6047 was that if broken,
a F.F.D. must always fail safe. The gas filled F.F.D.
will be better than the mercury F.F.D. in this respect,
as the chance of a blockage resulting in the capsule
remaining pressurized is much reduced. The method of
construction with the capsule attached to the valve plate
will be very good from this point of view, as the loss
of fill pressure will cause the capsule to pull the valve

plate down onto its seating with extra force.

To be reliable a F.F.D. should keep close to its calibrated
opening temperature throughout its life. However creep
of the rubber valve seal under the valve sealing force
provided by the capsule or spring would gradually reduce
the opening temperature. Fig. 49 shows the creep of
standard valve plates under a 10N load at different temp-
eratures and indicates that after a settling period of
approximately 1 hour, a creep rate of up to 0.0085 mm per
log decade can be expected. It will be seen that this
creep rate was not affected very much by temperature,
illustrating the usual finding that the creep rate of
rubber follows the same pattern at all temperatures, the
only difference being that the log time scale is shifted
(66).

It is suggested that F.F.D.s are calibrated to give the
required opening temperature after they have been shut
for a given period - say 10 hours. After this the rate
of creep against real time will be slow. For instance
under a 10N load the standard valve plate will have
compressed by a further 0.034 mm from its 10 hour
compression after 10 years of service. For F.F.D. 31
this would be approximately equivalent to a reduction
of 40 $^\circ$C in the opening temperature.

The creep rate is usually proportional to the amount
the rubber is compressed (66), which as fig. 46 illustrates
is linearly related to the load applied. Therefore
the lower the valve sealing force the less the creep
rate and if necessary a low creep valve could be made
using the separate valve plate method of construction
with a very light spring. For a F.F.D. with the valve
plate attached to the capsule, the valve plate sealing
force is fixed and can be calculated using the following
equation developed from equation 5.12:-

$$F = A_e \left\{ 101.3 + P_r - \frac{P_n T_e^2 (V_p + U)}{T_e \, 300 \, (V_p + U + \tfrac{1}{2}\pi r^2 b)} \right\} \quad \dots \quad (8.14)$$

Normally when the valve is fully shut, $T_e \sim 300 \,^{\circ}K$, therefore equation 8.14 can be simplified as follows:-

$$F = A_e \left\{ 101.3 + P_r - \frac{P_n (V_p + U)}{V_p + U + \tfrac{1}{2}\pi r^2 b} \right\} \quad \dots \quad (8.15)$$

where P_r is the pressure read from the capsule pressure-extension curve at the capsule extension, b, at which the valve shuts and A_e is the capsule pressure effective area. All the other variables are as defined in section 5.3. This equation gives the valve sealing force for F.F.D. 31 as approximately 10N.

8.8 Manufacture of the Gas Filled F.F.D.

Because of the similarity of the gas filled F.F.D. to the mercury F.F.D., very little change to the mercury F.F.D. production plant would be necessary to enable the gas filled F.F.D. to be manufactured. The only major change needed would be to the filling equipment for the thermal systems.

Fig. 60 illustrates the phial shape envisaged for a production F.F.D. and suggests a filling method. The phial and capillary are made separately and then brazed together, since this is far cheaper than a one piece construction. After brazing it is suggested that the assembly is heated to say 700 $^{\circ}C$ in a furnace to drive off all contaminants such as brazing flux and oil from the inside of the phial. The capsule would then be brazed to the capillary and the open phial end inserted into the filling rig as shown in fig. 60. After evacuating the thermal system is filled to the correct pressure with

helium and sealed by means of the two 'chisel' spot welder electrodes. The swaged down phial end is necessary for a good quality spot welded seal, as experience has shown that it is very difficult to seal large diameter tube in this way. For mass production purposes it is suggested that many thermal systems be filled at once by fitting them onto a rotary table. They could all be evacuated and pressurized simultaneously and then each thermal system could be swung beneath the spot welder electrodes for sealing.

Having been sealed, the thermal system would then be stroke tested by heated the phial in a flame and checking the movement of the capsule. If the stroke was within the correct limits the thermal system would then be fitted to a valve body. After this, the method of manufacture and testing would be very similar to that for existing mercury production.

CHAPTER 9

THE MARKETING CHANNEL FOR F.F.D.'S

9.1 The Theory of Marketing Channels

The F.F.D. manufacturers do not sell direct to the public,
therefore an industrial marketing channel exists. This
is a group of organizations who pass the product from
one to another, until it is eventually bought from the
last channel member by the "end user". Fig. 61 shows
how the marketing channel for cooker F.F.D.'s is organized.

The distribution of power (and perhaps more importantly
PERCEIVED power) in the channel is crucial, as it deter-
mines just how free each member is to make product,
marketing and pricing decisions. Rosenbloom (67) considers
that the basis for power in the market channel can be
of 5 different types:-

1) Reward power
2) Coercive power
3) Legitimate power
4) Referent power
5) Expert power

He defines each of these as follows:

Reward power. The capacity of each channel member to
reward another if the latter conforms to the influence
of the former.

Coercive power. Essentially the reverse of reward
power. In this case a channel member's power is based
on the expectation that the former will be able to punish
the latter if he fails to conform to the former's influence
attempts.

Legitimate power. This power base stems from internalized norms in one channel member, which dictate that another channel member has a legitimate right to influence him and that he has an obligation to accept that influence.

Referent power. When one channel member perceives his goals to be closely allied to, or congruent with, those of another member, a referent power base is likely to exist. Thus a channel member will find it easy to influence another member whose interests are very similar to his own.

Expert power. This base of power is derived from knowledge (or perception of knowledge) which one channel member attributes to another in some given area.

Another important factor determining interorganizational relationships in the marketing channel is the concept of "role". Rosenbloom (67) defines role as "a set of prescriptions defining what the behaviour of a position member should be". The role of each member will be closely associated with his own interests, thus the role of the F.F.D. manufacturers would be to increase the market share of their own particular brand of F.F.D.. Aside from such clear cut isssues, there is a grey area where interests overlap or conflict. In this case the roles of channel members could be defined when the channel is set up, or could develop with time. Many channels are very old (the F.F.D. channel ~15 years) and over the years channel conflicts develop, where members seek to change their role. The outcome of these conflicts will probably depend on the power distribution in the channel, but with time each channel member's "role perception" begins to coincide with his colleagues "role expectations" of him. Thus Ford (68) has found that "the role expectation structure is more clearly visible in long established channels, and the rigidity of member expectations increases with time" and that

"expectations eventually tend to become governed by a
code of ethics based on established practice".

9.2   The F.F.D. Channel

Ford (68) has studied the channel for gas central heating
appliances and has attempted to measure the balance of
perceived power in this channel. Members of each channel
level were questioned and a value assigned to the power
attributed by the respondents to each channel level. The
net power between two levels A and B was then calculated
by subtracting the power of A over B from that of B over
A. Fig. 62 shows the results from the point of view
of each channel level. The arrows indicate the direction
of the net power. These results are interesting, as all
perceived the Gas Board to have net power over each level.

Fig. 62 should now be compared with fig. 61, the marketing
channel for domestic cooker F.F.D.'s as it was in 1977.
It will be observed that British Gas is actually a member
of the last level of this channel, as it sells gas
appliances through its gas showrooms. In fact it will be
noted that the gas showrooms virtually monopolise the
last channel level, as in 1977 they accounted for 91%
of cooker sales. The situation for other gas appliances
is much the same and for instance in 1979 sales through
British Gas showrooms accounted for 88.5% of cooker sales,
86% of space heaters and 67% of instantaneous hot water
heater sales (69).

Thus referring to Ford's power measurements, it will be
appreciated that the power of British Gas in this channel
will be greatly enhanced when compared to the central.
heating channel. This is because as well as having the
same outside influence on the channel, it has extra
power bestowed upon it by its virtual monopoly of the
bottom channel level and as fig. 62 shows, this is one
of the most influential positions in the whole channel.

The high percentage of cookers retailed through British
Gas gives it an enormous reward and coercive power base,
which is made full use of. Any appliance must be "sales
listed" before it can be sold through a British Gas
retail outlet, thus the consequences of a "sales listing"
refusal for a product are obvious. To obtain "sales
listing", an appliance must be submitted to British Gas
for a safety and engineering evaluation. The appliance
must contain only "approved components", thus British
Gas by virtue of its channel dominance can control even
the component manufacturers producing F.F.D.s. British
Gas maintain that this situation is very much for the
public good, as being the supplier of gas, it must
exercise responsibility for safety, and "there cannot
in the Corporation's opinion be a clear cut distinction
between research into appliance development and research
into gas safety". (69)

9.3   The Investigation by the Monopolies and Mergers Commission

On December 1 1977 the Director General of Fair Trading
requested that the Monopolies and Mergers Commission
examine the supply of cookers, space heaters and instant-
aneous hot water heaters for the existence of a monopoly
situation (70). The commission published its report
in August 1980 (69) and one of the conclusions reached
was that the British Gas Corporation had a monopoly of
the supply of these goods to the public. The Commission
recommended that the British Gas Corporation's retail
outlets should either be sold off to the public sector,
or the accounting proceedures should be changed to prevent
the Corporation from using its monopoly power in appliance
marketing.

The Commission criticised the appliance manufacturing
industry for its lack of investment in buildings and

production plant and its failure to develop a significant
export market. The report (69) stated, "This seems to
stem chiefly from the dominant position of the B.G.C..
This is exercised in the first place as a monopoly buyer
and retailer, but the Corporation has additional weight
as the statutory monopolist supplier of the fuel. It
is therefore in a position to exercise a strong influence
over appliance design and manufacturers have found
themselves obliged to comply with the Corporation's
wishes as to the type of models produced, their design
characteristics and their promotion. It is our impression
that the manufacturers - even those which form parts of
groups with substantial manufacturing involvement in other
fields - have come to rely too greatly on the Corporation
for research and development, basic design, market
research and marketing, so that their own activity in
these fields is now inadequate for the nature of the goods,
and the changing demands of the final customer".

From this it is evident that besides having a reward and
coercive power base, British Gas also has legitimate,
and expert power base. It is also clear that the Corpor-
ation has a referent power base, as the success of the
manufacturers depends upon the ability of the B.G.C. to
market the appliances they make.

What then will happen to the market channel if, as the
Monopolies and Mergers Commission recommends, the British
Gas retail outlets are removed from its control? Ford
(68) has shown that in long established channels, members'
role expectations become rigidly fixed and thus any changes
would be expected to be slow. Also Ford's examination
of the gas central heating channel, where British Gas
do not act as a retailer, (builder's merchants do this),
has shown that the Corporation still has a very strong
influence. Thus if the Corporation lost its retail
outlets, its Reward and Coercive power bases would be
diminished, but the Legitimate, Expert, and Referent power

bases would still exist. This combined with the fixed
role expectations in the channel would tend to suppress
any dramatic change.

CHAPTER 10

THE F.F.D. MANUFACTURING INDUSTRY

10.1 Structure of the F.F.D Manufacturing Industry

Fig. 61 illustrates the structure of the gas cooker F.F.D.
manufacturing industry as it was in 1977. There were
three major manufacturers in competition, Harper Wyman Ltd
(part of the American group Oak Industries), Teddington
Controls Ltd (part of the British group United Gas
Industries) and Concentric Controls Ltd. There were
also two other minor manufacturers, T.I. Gas Controls
Ltd, who made F.F.D.'s for the T.I. range of gas cookers
from parts supplied by Harper Wyman and Drayton Controls
Ltd, who made F.F.D. thermal systems only. Fig. 61
gives the relative market shares of these companies
(except for Drayton, which had a very small market share).
All were involved in making other types of gas controls
such as thermostats and gas cocks, as well as manufacturing
F.F.D.s.

The majority of the F.F.D.'s made by these companies
are of the mercury type, which has as yet suffered from
very little import competition. The mercury F.F.D. is
not used in Europe and consequently the European manu-
facturers have no production capacity for the manufacture
of this device. The U.S.A. however, has a large mercury
F.F.D. industry, the market leaders being Robertshaw,
White-Rogers and Harper Wyman.(the U.S.A. parent company),
but as yet there have been very few imports into the U.K.
from these sources.

Although British domestic cookers are mainly fitted with
the mercury F.F.D., most other appliances use thermo-
electric F.F.D.s. The thermoelectric device is manu-
factured widely on the continent and British manufacturers

have suffered intense low priced competition from Spain
(Copreci), Italy (S.I.T.) and Germany (Junkers). The
British industry has now found itself unable to compete
on price terms and at present almost 100% of the thermo-
couples and coils for thermoelectric F.F.D. assemblies
are imported.

10.2 The History of Harper Wyman Ltd

This company began just after the war as Star Engineering
Ltd and manufactured a variety of gas taps. In the
mid-1960's this company was acquired by the American
manufacturer of gas controls, Harper Wyman, who wished
to use Star as a vehicle for marketing its designs of
thermostat and F.F.D. in the U.K. Expertise and manu-
facturing equipment were sent from the United States and
Harper Wyman Ltd (as Star eventually became) was amongst
the first U.K. manufacturers of mercury F.F.D's. During
the early 1970's, the American parent company was
acquired by Oak Industries Inc., a large American
conglomerate with investments in a wide range of industries
and Harper Wyman Ltd was consolidated into the Oak Group
accounts. Oak Industries already owned another British
manufacturer, Diamond H Controls Ltd, a company which
manufactured electric controls such as relays, thermostats,
and "simmerstats" for electric cookers. The two British
companies were not closely associated, despite their
common ownership, although Diamond H did manufacture some
parts for the Harper Wyman thermostat.

Harper Wyman Ltd had gradually expanded during the 1970's
from a total sales value of £135,000 in 1971 to £1,250,000
(approximately £656,000 at 1971 prices) in 1979. However
company profitability remained low, so in 1980 Oak
Industries decided to rationalize its U.K. operations, by
closing down the Harper Wyman factory at Malvern Link
which employed approximately 100 people, and transferring
production to the much larger Diamond H facility at

Norwich which employs approximately 1,000 people. As
the Diamond H name was not well known in the gas industry,
the Harper Wyman name was to be retained for the gas
controls produced by Diamond H.

CHAPTER 11

THE MARKETING STRATEGY OF HARPER WYMAN

11.1 Distinguishing Features of Industrial Marketing

Webster (71) has stated that the "hallmark" of industrial
marketing is a close buyer-seller relationship, unlike
consumer marketing, where these relationships are brief
and more often than not end with the sale. In an
industrial marketing situation the buyer depends upon
his supplier for an assured supply of components of the
right quality and price, with efficient order handling
and delivery. Getting all of these components of the
deal right requires much negotiation, and a continual
relationship between buyer and seller. Thus to quote
Webster, "the actual transaction is only one point on
the time continuum in industrial marketing" (71). It
is clear then that the buyer is not looking for just a
product from his supplier, but a service as well, thus
effective selling in industrial markets depends upon all
parts of the organisation (e.g. the manufacturing, research,
development, inventory control and engineering departments)
working efficiently together, hence industrial marketing
is marked by its greater "functional interdependence"
than consumer marketing.

Industrial buyer behaviour is considerably different
from consumer behaviour and in developing a marketing
approach this must be taken into account. The industrial
buying decision making process is a complex one, as it
involves many people, complex economic and technical
factors must be considered in detail and the formal
organisation within which the buyer works has an influence.
Because of these factors, industrial buying decisions
take a long time and need much consulatation, thus the
selling organisation must expect to put in a lot of market-

ing effort and then expect a large time lag before any
buyer response.

Finally the product itself is more complex than in
consumer marketing. Webster has stated, "the product is
not a physical entity per se. Rather the product is an
array of economic, technical and personal relationships
between the buyer and seller". Thus the marketer must
be willing to discuss with the potential customer and if
necessary change the product and the terms under which
it is offered to suit the customer.

11.2   Development of a Marketing Strategy

A corporate strategy must be developed to enable a company
to make a consistent approach to marketing itself and its
products. Webster (71) has suggested that any strategic
planning process should have the following seven components:-

a)   An appraisal of the strengths and weaknesses of
the firm.

b)   The creative definition of the firm's distinctive
competence.

c)   An assessment of the economic market environment
and how it is changing.

d)   The definintion of long-term goals.

e)   The identification of specific market and product
opportunities available to the firm, given its capa-
bilities, and the selection of those to be persued.

f)   The setting of specific, measurable objectives
required to achieve long-term goals.

g)   The development of programs for exploiting
defined opportunities and meeting those objectives.

A strategic plan should allocate a company's resources
such that the maximum use is made of the strengths in the
organisation and so minimum exposure is given to its
weaknesses. Clearly such a planning exercise will also

define areas to which the company should commit resources
so as to improve its capabilities.

11.3 Marketing at Harper Wyman Ltd

The Marketing Director at Harper Wyman considered that
the main strength of the company was its ability to change
its products to meet its customers needs and that this had
made a major contribution to the company's sales. In his
opinion both major competitors (Concentric and Teddington)
were not so flexible and tended to offer standard products
on a "take it or leave it" basis. This strategy of flex-
ibility was incorporated into the company structure, when
in 1978 the marketing director also took on responsibility
for new product development. It was considered that this
would give increased efficiency in converting customers'
needs into new or modified products.

Selling was conducted very much on a personal relationship
basis solely by the marketing director. He considered
that this was possible because the company only dealt
with a total of approximately 40 regular customers (only
one of whom purchased F.F.D.'s) and about 12 peripheral
customers. Of the regular customers, one (Valor) accounted
for 22% of the company's sales. The director attempted
to visit each customer at least once per year. Some
exporting was done by the company and one notable achieve-
ment was the exporting of refrigerator gas taps to
Electrolux of Sweden. It had taken Harper Wyman six
years with many visits and quotations before it was accepted
as an established supplier. This example was very much
the exception, as in general little effort was put into
export marketing.

Most customers operated with very low stock levels and
for example Valor operated with one month's supply of
parts while Potterton worked on the basis of only three
day's supply. To facilitate the efficient handling of

customers' orders, works scheduling, and delivery, Harper
Wyman installed a new mini-computer based stock control
system in 1980, however the company closed before this
new system had realised its full potential. The majority
of customers preferred to double or triple source when
buying F.F.D.s and thus interchangeability between the
different manufacturer's products was an important customer
requirement. Unfortunately whilst the products of
Concentric or Teddington were directly interchangeable,
the Harper Wyman F.F.D. had a differently shaped phial
requiring a different fixing. Because of this, direct
F.F.D sales made by Harper Wyman had dropped from 13%
of the market in 1977 to only 6% in 1979, and in fact
most production went to Valor which single sourced from
Harper Wyman. Thus F.F.D.s had been "squeezed in signif-
icance" and the importance of F.F.D.'s in relationship
to the company's other products can be gauged from the
following table of sales values for 1979.

PRODUCT	TOTAL SALES VALUE (1979)
Thermostats	£570,000
F.F.D.s	£ 80,000
Gas Cocks	£500,000
Central Heating Valves	£100,000 (Source Harper Wyman Ltd)

The marketing director recognised that the phial shape
was limiting the sales of an otherwise good product and
in his new role as director of new product development
initiated the design of the "mini-bulb" F.F.D. which was
directly interchangeable with the competition's products.
It was hoped that his new product would produce a
considerable rise in the Harper Wyman share of the F.F.D.
market, but the company closed before this new product
could get into production, although production of this
device is now being taken up by Diamond H Controls Ltd.

11.4 Analysis of Harper Wyman Marketing Strategy

It is instructive to examine the corporate strategy of
Harper Wyman in the light of Webster's seven point
planning process. (See section 11.2).

The basic strength of the company was its ability to
machine small metal parts and assemble them into finished
valves. Harper Wyman had two main weaknesses, the first
of which was that there was only one draughtsman and one
one non-graduate engineer to assist the marketing manager
in the product development programme. The other weakness
of the company was the age of the production plant which
tended to preclude high productivity manufacturing methods.
Since the original equipping of the factory to make
F.F.D.s, the American parent company had allowed little
investment in the factory.

The marketing director had identified the company's
"distinctive competence" (defined by Webster as "a
product-market strategy which distinguishes the firm
from its competitors in some way important to its customers")
as "flexibility", meaning that Harper Wyman was willing
to modify its products (e.g. modifying F.F.D. valve bodies
to suit customers' requirements) to meet customer require-
ments. However such a marketing approach would put
greater strain on the development department due to the
higher work load, and the fact that due to "functional
interdependence" the development department would be in
the "front line" of the marketing effort. Despite the
fact that this marketing strategy highlighted the small
amount of development effort available, the marketing
manager was convinced that the "flexibility" strategy
contributed to sales.

When considering mercury F.F.D.s the "assessment of the
market environment and how it is changing" revealed two
things. The first was the need for a product which was

interchangeable with its competitors to restore the eroded
market share and the first "goal" was the introduction of
such a product. Unfortunately due to the reduced signif-
icance of F.F.D.s in Harper Wyman's output, limited design
effort had to meet higher priorities (such as thermostat
development) first, so the new design was slow in coming
to fruition, allowing the Harper Wyman market share to
drop as low as 6%. In the longer term there was the prospect
of British Gas banning mercury F.F.D.s. Here was the
threat of the loss of £80,000 per annum production, (more
if the new F.F.D. succeeded), but the opportunity of a
much larger production if an acceptable alternative to
the mercury F.F.D. could be developed. The company
could not afford to commit scarce financial and design
resources to such a high risk venture, so the project
was "farmed out" to Bath University, leading to the present
research. The "measurable objectives" of this programme
would be the development of a mercury-free F.F.D.,
acceptable to both British Gas and the customer.
Finally the "programme for exploiting defined opportunities"
would be the production and marketing of the mercury-free
F.F.D. if it proved acceptable.

Turning now to buyer-seller relationships, it was outlined
in section 11.1 that industrial marketing is marked by
the closeness of buyer-seller relationships, thus success-
ful industrial marketing must require a great amount of
marketing effort on the part of the seller. With 40
regular customers to look after, the Harper Wyman
marketing manager would need all of his time to maintain
regular contacts (he tried to visit customers once per
year), as well as looking after his new product develop-
ment responsibility. The development of new buyer-seller
relationships especially in the export markets, is an
extremely time-consuming process and the marketing
director would have little time for the regular contacts
and follow up needed. Thus the company had little
commitment to developing new markets, especially in the

export field.

However as noted in section 10.2, Harper Wyman Ltd (Malvern
Link) closed down in 1980 and although there were some
rationalization reasons for this decision, the main
reason was that the profitability of the company did not
justify its continued existence. The major cause of this,
in the opinion of the author, was the failure of the
company marketing strategy to develop sufficient market
share to keep unit costs down. It has been noted how
the share of the F.F.D. market had fallen from 13% to 6%
and this would increase unit costs tending to depress
market share even further. The antiquity of the production
plant, although causing occasional quality problems and
needing extra staff to run and maintain it was of second-
ary importance as a cause of the company's failure. This
was because the costs of the plant had been written off
long ago and the introduction of new machinery would have
demanded large improvements in productivity to pay for
it.

The way out of this downward spiral was to develop new
products and new markets, but as has been pointed out,
doing this needed high quality technical personnel and
more marketing manpower, which the company did not possess.
In developing new products for the gas industry the
situation was made worse by the safety and engineering
evaluation required by British Gas which lengthened new
product development times and took up the time of
technical staff. Clearly extra technical staff and to
a lesser extent more marketing effort was required, but
the necessary personnel needed would have to be of high
quality and therefore expensive. Unfortunately the
pay-off time from this manpower investment would have
been long and no financial help was available from Oak
Industries. Possibly the only was out of the situation
would have been a reduction in the production staff by
streamlining the production operation and using the

salaries saved to pay for the technical staff needed for
product development. This was not done and the management's
failure to make the employment of high quality development
engineers a high priority, plus their choice of a market-
ing strategy which highlighted the company's weakness,
must be regarded as a major factor in the failure of the
company.

CHAPTER 12

MARKETING THE GAS FILLED F.F.D.

12.1   The New F.F.D. - Success or Failure?

The chances of a new product succeeding in the market
place are very low. Cooper (37) states that in 1974
an estimated 30,000 new products were introduced
onto the American market, but of these, 80% were not
on the market one year later. Booz, Allen and Hamilton
(72) have shown that for every 6 man hours spent on
industrial R and D, 5 of these hours were spent on
products that failed or were cancelled.

In an ideal world, it would be possible to identify
in advance products which would succeed. This of
course is not possible, but new products can be
examined with respect to marketing theory and the
conditions prevailing in the market place to identify
those which have a higher probability of market success.

Much research has been done to identify just what
separates new product failures from successes and
many different parameters have been identified which
could be important. . Cooper in his "project Newprod"
(37, 38) found 18 "dimensions" which characterised
new product projects. When related to new product
outcomes, it was found that there were three "dominant"
dimensions, which were a determinant of new product
success. These were:-

   1)   Product uniqueness - superiority

2)   Market knowledge and marketing proficiency

3)   Technical and production synergy - proficiency

Cooper analysed almost 200 new products, half of
which were successes and half of which were failures.
He found that of the new products which were "high"
on all three factors (see above), 90% were successes
and for new products with a "low" rating on all
three factors only 7% could be classed as successes.
Moreover Cooper discovered that these three factors
were important determinants of success "regardless
of the type of venture or type of firm".

Because of this it is instructive to analyse the
new F.F.D. project with regard to these three factors.
Firstly considering "Product uniqueness - superiority",
the device developed in the present work would
clearly have the advantage in the customers' eyes
of being like the mercury device, but without the
problem of mercury and at the present time this
F.F.D. is unique in that there are no other devices
offering this advantage. "Technical and production
synergy - proficiency" brings in the question of
the abilities of the company intending to produce
the product, which in this case would be Diamond H
Controls Ltd, as the successor to Harper Wyman Ltd.
Diamond H has a long history in the production
of small components for the electric cooker industry,
in particular one of their products, the electric
cooker thermostat, is very much like the new F.F.D.
as it contains a capsule - phial thermal system.

In fact Diamond H, unlike Harper Wyman Ltd.,

has a facility for the production and welding of nesting
capsules and has much experience in this area. Further-
more, since Diamond H has now taken over mercury F.F.D.
production from Harper Wyman, the company will have
gained more experience in the production of these devices
by the time the new F.F.D. is ready for production. Thus
the new F.F.D. project and Diamond H will have a high
technical and production synergy.

Finally we come to "market knowledge and marketing prof-
iciency". Here Diamond H with its knowledge of marketing
in the differently organized electric cooker industry
would be at some disadvantage, however again by the time
the new product could go into production, Diamond H would
have gained proficiency by selling Harper Wyman products
to the gas industry. Before money can be committed to
the new product "market knowledge" must be gained to
assess the likely market for the new F.F.D.. "Market
knowledge" covers many things, but two will have a great
bearing on the likelihood of new product success:-

1) The size of the market, or market segments which
the new product is suitable for when sold at a profit.
2) The likely rate of acceptance of the new product
by the market.

These two parameters will now be considered in detail.

12.2 Market Potential of the New F.F.D.

Baker (73) suggests that before a new product reaches the
market place, the innovator should have undertaken a
thorough demand analysis and must have:-

a) Identified potential users of the innovation.

b) Projected minimum/maximum levels of usage under
various circumstances.

c) Selected the market segment with the greatest
incentive to adopt the innovation as the target for
his initial marketing efforts.

Fig. 63 shows the size and trends in various gas appliance
market segments in the United Kingdom. Clearly, since
the new F.F.D. is designed to replace the mercury F.F.D.,
the segment with the greatest incentive to adopt the
innovation will be that into which the mercury device is
now sold, i.e. the gas cooker segment. Fig. 63 reveals
that this segment has stabilized at about 600,000 units
per annum and it is hoped that if the new F.F.D. lives
up to its promise then this will be the minimum market
size.

Possibly the new product may be marketed in other segments.
Except for very small boilers, the device would not be
suitable for the central heating segment, (unless developed
into a flame switch) and the same applies to the instant
water heating segment. The space heater segment is very
large indeed and consists mainly of wall mounted radiant
gas fires. The new F.F.D. as envisaged at present would
not have sufficient flow capacity for the larger fires,
but if high flow versions were developed, then this device
would be suitable for the whole segment. At the present
time radiant fires are not fitted with F.F.D.'s, but with
improving safety standards, this could well be a thing
of the future. In fact in offering a simple, automatic,
mercury-free F.F.D. system, the new device could precip-
itate the fitting of F.F.D.'s in this segment. To
summarize, the likely market in the United Kingdom would
certainly be up to 600,000 units per annum, with possibly
another 900,000 units per annum if the market developed
fortuitously.

Initially, U.K. marketing will be of prime interest, but

later the possibility of developing export markets should
be considered. Here the possibilites are enormous, and
for instance the size of the United States mercury F.F.D.
market has been estimated at 2,000,000 units per annum.
(74). In Europe, as has been explained earlier, there is
at present no mercury F.F.D. market and here the new
device might be expected to develop the market share
that the mercury F.F.D. now enjoys in the U.K. and U.S.A..

12.3 Market Acceptance of the New F.F.D.

Rogers (75) has proposed that the following innovation
characteristics will have an affect on the rate of
adoption of that innovation by the market.

    a)   Relative advantage
    b)   Communicability
    c)   Compatibility
    d)   Complexity
    e)   Divisibility

Although Rogers was primarily considering the rate of
adoption by the market, clearly the product attributes
listed above also determine its success. A product with
a low scoring on Roger's criteria would be taken up so
slowly by the market, that only a low market share would
be achieved by the time the decline part of the life
cycle were reached. Thus the above product attributes
are crucial in deciding the success of a new product.

The market itself will have an affect on the acceptance
of the new product and for instance such factors as the
buyer behaviour and resistance to change found in the
market place are important. However, because the resistance
to the new product will vary from company to company, the
marketing organization can seek out the "innovators" and
"early adopters" (73) and make them the target of early
marketing effort, which if successful will bring about

the first sales of the product. Later the strategy can
be adjusted to try to modify the opinion of the "early
majority", "late majority" and "laggards" to the new
product and thus increase sales. The point here is that
to some degree the market reaction to the device can be
taken cognisance of and manipulated by the marketing
organization. On the other hand in the case being
studied here, the new product's attributes are diffucult
to change, being determined by the limited variability
of the new F.F.D. for technological reasons and the state
of the market as it exists at present. Because they are
so fundamental, the new F.F.D.'s characteristics will now
be studied in detail.

12.3.1   Relative Advantage

Baker (73) describes relative advantage as the "benefit
conferred on, or available to the adopter of an innovation,
adjusted to take cognisance of the adopter's present
'economic status'".

The mercury F.F.D. has been used for many years in gas
cookers and in the main has proved both safe and reliable,
thus the relative advantage for the cooker O.E.M.'s in
changing to the new F.F.D. are not high. The end user of
the cooker, usually a home owner, is more interested in
the functionality, reliability and appearance of the
cooker, rather than such details as the type of F.F.D.
fitted, although if it became widely known that the F.F.D.
contained mercury, more than a few users would probably
become worried. Therefore there has been little pressure
for change either from the O.E.M.'s or the end users and
in fact the motivation for change has come entirely from
the British Gas Corporation. British Gas were extremely
worried about possible toxic effects caused by mercury
leakage and the possibility of adverse publicity for gas
cookers, so they have been encouraging the F.F.D.

manufacturers to improve their products and develop a
new mercury-free F.F.D.. Moral pressure from British
Gas on the cooker manufacturers would certainly help
increase the "relative advantage" of fitting the new
F.F.D.. If British Gas were to take the ultimate step of
banning the mercury F.F.D. then the "relative advantage"
of the new F.F.D. would become enormous, since it would
be the only device which would simply substitute for the
mercury device.

In export markets currently using the mercury F.F.D. (e.g.
U.S.A. and Canada) the relative advantage of the new
device would be dependent upon the strength of worries
about mercury. In markets not using the mercury F.F.D.
the "relative advantage" would be large since for the
first time they would be able to enjoy the benefits of
the mercury device (simple, automatic, no electricity
supply needed) without the mercury.

12.3.2 Communicability

This is the degree to which the benefits of using the new
innovation are observable and desirable to others. The
greater this factor is the more rapidly the innovation will
diffuse into the market place. For a simple component such
as the new F.F.D., the communicability should be high.

12.3.3 Compatibility

Compatibility is the "degree to which an innovation is
consistent with the existing values and past experiences
of the adopters" (73). Thus for markets conditioned to
using the mercury F.F.D., this is very high indeed, and
this factor should aid rapid diffusion of the new F.F.D..
In markets where mercury F.F.D.'s have not been used this
would be a barrier to acceptance.

12.3.4 Complexity

This is the degree to which the new innovation is difficult to understand or use. Clearly for this device complexity will prevent no barriers to its diffusion.

12.3.5 Divisibility

This is the extent to which an innovation can be tried on a limited basis. With this device, cheap small scale trials are no problem and this should be a great aid to diffusion.

The following chart summarizes the new F.F.D.'s characteristics in markets where mercury F.F.D.s have been used, and where they have not.

NEW F.F.D. CHARACTERISTICS AS AN ADOPTION DETERMINANT

+ = Characteristic aids diffusion
N = Characteristic does not affect diffusion
- = Characteristic retards diffusion

CHARACTERISTIC	MARKETS USING MERCURY FFD	MARKETS NOT USING MERCURY FFD
Relative Advantage	N (+ if mercury prohibited)	+
Communicability	+	+
Compatibility	+	-
Complexity	+	+
Divisibility	+	+

Thus assuming that the new F.F.D. lives up to its promise
as a substitute for the mercury F.F.D., then the barriers
to its diffusion into the market place do not seem very
high.

12.4 The Future

Responsibility for the new F.F.D. has now passed to
Diamond H Controls Ltd., although the products are still
to be marketed under the Harper Wyman name to help
ensure continuity. Diamond H is a large and successful
company which has a good track record in the develop-
ment and marketing of new electric controls. This
augurs well for the new F.F.D. as Harper Wyman, with
its very limited new product development capability
would have had much difficulty in developing this device
to the point where it satisfied British Gas and was ready
to be mass produced.

As has previously been noted, Diamond H has little
experience marketing in the gas industry. However this
is changing and at the time of writing the company has
been producing gas thermostats and F.F.D.s for some six
months and is rapidly gaining experience. Indeed, it now
appears that customers whom Harper Wyman had lost are
showing renewed interest in the products as produced
by Diamond H. In part this may be due to the fact that
Diamond H is a much larger organization with more resources,
which projects a better image into the market place,
instilling more confidence into the customers. Customer
confidence in industrial marketing is of paramount
importance, as the customer depends heavily upon his
suppliers. In this way Diamond H is able to compete in
the market on an equal basis with Teddington and Concentric,
which are both large organisations.

The new F.F.D. is at present being developed for production
and by the time it is ready for sale it is anticipated

that Diamond H will be well ensconced in the market, with
a higher market share than was previously enjoyed by
Harper Wyman. By this time also, the company will have
become fully experienced in gas control marketing. There-
fore it is the opinion of the author that the new F.F.D.
will have a much greater chance of success with Diamond H
than it would have enjoyed with Harper Wyman.

Applications for U.K. and foreign patents have been
submitted by the inventors (Harrison, Reiter and Diprose)
and Bath University for the gas filled F.F.D.. It is
intended that Diamond H be given exclusive rights to
exploit the patents and levy royalties. If the applications
result in strong patents, then this could add flexibility
to the Diamond H marketing policy. For instance in
foreign markets where the company had little marketing
expertise, Diamond H could license a local manufacturer
to make the device on payment of royalties. In the U.K.,
where customers usually multi-source, it could well be
prudent to license other U.K. manufacturers to make the
device.

CHAPTER 13

CONCLUSION

13.1 Engineering Conclusions

It has been demonstrated that the gas filled F.F.D. can
be made with a sufficiently good performance to substitute
for the mercury F.F.D.. Tests completed on prototypes
have shown that the gas filled F.F.D. should certainly
have sufficient reliability to be used in a cooker oven.
Without the effects of mercury leaching the phial walls,
the life of a well-made gas filled F.F.D. should greatly
exceed that of the mercury F.F.D.. The speed of operation
of the prototypes was well within that specified by BS 5258
(table 5) and there is no fundamental reason why all of
the requirements of BS 6047 part 1 should not be met. In
section 5.1, which looked at the features needed by an
alternative to the mercury F.F.D., the following require-
ments were suggested:-

a) It must be cheap to make

b) It must be self contained and not need an
electricity supply

c) It must open and shut automatically

d) It must have a flexible connection between the
sensor and valve

It will be seen that the gas filled F.F.D. meets require-
ments b, c and d and, as it contains almost the same
components as the mercury F.F.D., any cost differences
between the two devices will be minimal. In fact the
new F.F.D. is so like the mercury F.F.D., it is almost
a direct replacement for it, the only difference being
the larger phial which may necessitate a larger fixing
bracket.

In section 5.1 further requirements were suggested, which

would make the F.F.D. suitable for appliances other than
cookers:-

 e) It must be able to sense standing pilots without
premature breakdown

 f) It must have a high cycle life

 g) It should have a high gas flow capability, if
possible up to 3 cubic metres per hour at 0.75 mb
pressure differential

 h) It should have a faster response time than that
of bimetallic, thermoelectric or mercury devices.

The long life requirements e and f could be met by using
a thermal system with a thick walled phial (say 1 mm or
2 mm thick). Such a thermal system could then be used in
boilers, sensing a standing pilot (requirement e), or
the cycling main burner flame (requirement f), depending
upon which was most suitable for the application in
question. This development of the gas filled F.F.D. might
well exceed the life of the thermoelectric F.F.D. (which
is not very long) and bring the advantages of the totally
automatic F.F.D. to boilers.

Requirement g is necessary to cope with the high gas
inputs needed by most other appliances. The experimental
prototypes built used the standard 25 mm diameter valve
plate, designed for use with the high stroke mercury
thermal system. This could be developed to give higher
flows by increasing the valve plate diameter, or going
to a "double beat" valve, or using levers to magnify the
capsule movement. Even so it is doubtful if this type
of F.F.D. could ever meet the flow requirement of a large
boiler. However, as boilers mainly have electric control
systems (with solenoid valves to control the gas), the
development of a gas filled "flame switch" should be
attempted. Diamond H Controls Ltd., with its electric
control experience, should be very well equipped to make

this development, which would be well worth while, as the central heating boiler market is approximately 500,000 units per annum (fig. 63). In fact, as the use of electronic control systems is likely to increase in the future, the market growth for a flame switch could well be large.

The speed of response of the gas filled F.F.D. is similar to that of the mercury F.F.D., but this is sufficiently good for most domestic appliance purposes. It is suggested that the gas filled F.F.D., being much less inclined to block in the manner of the mercury F.F.D., would be unlikely to become slow in operation with use, or fail in the open position.

13.2 Marketing Conclusions

The marketing analysis revealed the considerable power that British Gas had in the market channel and that this power is likely to continue despite, as now seems likely, its being divested of its retail outlets. Given that British Gas originally voiced the worries about the mercury F.F.D., it is assumed that this power will be to the advantage of the new device. In section 12.2 the substantial size of the possible market was pointed out, especially if the F.F.D. was developed to be suitable for other appliances. The analysis of the likely market acceptance of the device (section 12.3) showed there to be no significant barriers for the new F.F.D. to overcome, either in U.K. markets, or export markets. The possibility of exporting this F.F.D. to markets where the mercury F.F.D. has not been acceptable should be explored, as for the first time a totally automatic F.F.D. is available without the disadvantage of mercury.

At the time of writing, (August 1981), production proto-types are being prepared by Diamond H Controls Ltd., and

when ready, these will be submitted to British Gas for
approval. In conclusion, it is considered that there is
no reason why, given competent development,production
and enthusiastic marketing, the gas filled F.F.D. should
not succeed in the market place.

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APPENDIX 1

PROGRAM ffd.basic

```
                    PROGRAM FFD.BASIC
00100  '  ------------------------------------------------------
00110  ' ------------------------------------------------------
00120  '   CALCULATES CAPSULE EXTENSION AT DIFFERENT PHIAL TEMPERATURES
00130  '   CAPSULE PRESSURE EXTENSION DATA TAKEN FROM SPECIFIED FILE
00140  '   PERFORMANCE DATA PUT IN FILE "output"
00150  '   PERFORMANCE DATA ALSO PUT IN FILE "file31"
00160  '
00170  ' ------------------------------------------------------
00180  '
00190  file #2: "output"
00200  file #3: "file31"
00210  scratch #2
00220  scratch #3
00230  print #2: "DATE OF COMPUTATION        ",dat$
00240  print "TYPE NAME OF PRESSURE-EXTENSION DATA FILE"
00250  input z1$
00260  file #1: z1$
00270  print "INPUT  PHIAL VOL (mm^3), CAPSULE RAD (mm), FILL PRESSURE (KPa ABS), DEAD VOL. (mm^3),
START PRESSURE (KPa) "
00280  input v,r,p,u,o
00290  p=p-101.325
00300  s=0.5
00310  print #2: "  "
00320  print #2: "  "
00330  print #2: "PHIAL VOLUME mm^3               =",v
00340  print #2: "CAPSULE RADIUS mm              =",r
00350  print #2: "FILL PRESSURE KPa GAUGE        =",p
00360  print #2: "DEAD VOLUME mm^3               =",u
00370  print #2: "START PRESSURE KPa             =",o
00380  print #2: "  "
00390  print #2: "  "
00400  dim h (40,2)
00410  mat h=zer
00420  i=1
00430  if end #1 goto 520
```

```
00440 input #1: p1,e1
00450 h(i,1)=p1
00460 h(i,2)=e1
00470 i=i+1
00480 if i=40 goto 500
00490 goto 430
00500 print "TOO MUCH DATA IN FILE"
00510 goto 1110
00520 p1=0
00530 e1=0
00540 for j=1 to 40
00550 p2=h(j,1)
00560 e2=h(j,2)
00570 if p<=0 goto 610
00580 if p2<p1 goto 670
00590 if p>p2 goto 640
00600 if p<=p2 goto 690
00610 y=0
00620 p=p+101.325
00630 goto 730
00640 p1=p2
00650 e1=e2
00660 next j
00670 print "NOT ENOUGH DATA"
00680 goto 1110
00690 y=e1+(p-p1)*(e2-e1)/(p2-p1)
00700 e=y*r*r*s*3.1416+u+v
00710 p=(p+101.325)*e/(v+u)
00720 p3=int(p*10^3+0.5)/10^3
00730 print #2: "NOMINAL FILL PRESSURE KPa  =",p3
00740 print #2: " "
00750 print #2: " "
00760 print "TEMP DEG C","STROKE","TOTAL EXTENSION"
00770 print #2:"TEMP DEG C","STROKE","TOTAL EXTENSION"
00780 b=0
```

```
00790 t=300
00800 gosub 1200
00810 if z=w goto 970
00820 if z>w goto 850
00830 b=b+0.1
00840 goto 800
00850 b=b-0.01
00860 if b<0 goto 910
00870 gosub 1200
00880 if z<w goto 920
00890 if z=w goto 970
00900 if z>w goto 850
00910 b=0
00920 b=b+0.001
00930 gosub 1200
00940 if z<w goto 920
00950 if z=w goto 970
00960 if z>w goto 970
00970 b=int(b*10^3+0.5)/10^3
00980 t1=t-273
00990 g=b-y
01000 g=int(g*10^3+0.5)/10^3
01010 print t1,g,b
01020 print #2:t1,g,b
01030 print #3:using"-#####,-##.####",t1,g
01040 if t<301 goto 1070
01050 t=t+50
01060 goto 1080
01070 t=323
01080 if t>1100 goto 1110
01090 b=0
01100 goto 800
01110 print "ANY MORE DATA? -ANSWER y OR n "
01120 input z2$
01130 reset
```

```
01140 if z2$="y" goto 240
01150 stop
01160 '
01170 '
01180 '
01190 '
01200 rem pressure calc subroutine follows
01210 d=b*r*r*s*3.1416
01220 a=t*300*(v+u+d)
01230 c=v*300+t*(u+d)
01240 f=a/c
01250 m=p*(v+u)*f/(300*(v+u+d))
01260 w=m-o-101.325
01270 p1=0
01280 e1=0
01290 for j=1 to 40
01300 p2=h(j,1)
01310 e2=h(j,2)
01320 if e2<e1 goto 1410
01330 if b>e2 goto 1360
01340 if e2=0 goto1360
01350 if b<=e2 goto 1390
01360 e1=e2
01370 p1=p2
01380 next j
01390 z=p1+(b-e1)*(p2-p1)/(e2-e1)
01400 return
01410 print "NO MORE DATA FOR SUBROUTINE"
01420 goto 1110
01430 end
```

APPENDIX 2

FILE output

The data shown is for thermal system number 31.

DATE OF COMPUTATION   07/21/81

PHIAL VOLUME mm^3   = 500
CAPSULE RADIUS mm   = 9
FILL PRESSURE KPa GAUGE = 164.675
DEAD VOLUME mm^3   = 60
START PRESSURE KPa   = 0

NOMINAL FILL PRESSURE KPa = 288.88

TEMP DEG C	STROKE	TOTAL EXTENSION
27	0	0.379
50	0.037	0.416
100	0.11	0.489
150	0.173	0.552
200	0.228	0.607
250	0.277	0.656
300	0.316	0.695
350	0.352	0.731
400	0.384	0.763
450	0.413	0.792
500	0.437	0.816
550	0.458	0.837
600	0.477	0.856
650	0.495	0.874
700	0.512	0.891
750	0.527	0.906
800	0.541	0.92

APPENDIX 3

PROGRAM var.basic

```
                        PROGRAM VAR.BASIC
00100  ' !--------------------------------------------------!
00110  ' !                                                  !
00120  ' !                                                  !
00130  ' !  COMPUTES VARIATION OF CAPSULE EXTENSION WITH AMBIENT TEMPERATURE
00140  ' !  COMPUTES VARIATION OF Ts WITH AT. PRESS. AND AMB. TEMP.
00150  ' !  CAPSULE PRESSURE EXTENSION DATA TAKEN FROM SPECIFIED FILE
00160  ' !  RESULTS PUT IN FILE "voutput"
00170  ' !  RESULTS ALSO PUT IN "file32"
00180  ' !                                                  !
00190  ' !--------------------------------------------------!
00200  '
00210  print "TYPE NAME OF PRESSURE-EXTENSION DATA FILE "
00220  input a1$
00230  file #1: a1$
00240  print "INPUT V(mm^3),R(mm),Pf(KPa ABS),U(mm^3),O(KPa),Ts(DEG C) "
00250  input v,r,p,u,o,t
00260  t=t+273
00270  p=p-101.325
00280  s=0.5
00290  print "Te deg C","TOTAL EXT."
00300  file #2: "voutput"
00310  scratch #2
00320  file #3: "file32"
00330  scratch #3
00340  print #2: "DATE OF COMPUTATION         ",dat$
00350  print #2: " "
00360  print #2: " "
00370  print #2: "PHIAL VOL mm^3            =",v
00380  print #2: "CAPSULE RAD. mm           =",r
00390  print #2: "FILL PRESSURE KPa GAUGE   =",p
00400  print #2: "DEAD VOLUME mm^3          =",u
00410  print #2: "START PRESSURE KPa        =",o
00420  print #2: "OPENING TEMP. (Ts), DEG C =",t-273
00430  print #2: " "
00440  print #2: " "
```

```
00450 print #2: " "
00460 print #2:"Te deg C","TOTAL EXT."
00470 dim h(40,2)
00480 mat h=zer
00490 i=1
00500 if end #1 goto 590
00510 input #1: p1,e1
00520 h(i,1)=p1
00530 h(i,2)=e1
00540 i=i+1
00550 if i=40 goto 570
00560 goto 500
00570 print "TOO MUCH DATA IN FILE"
00580 goto 930
00590 p1=0
00600 e1=0
00610 for j=1 to 40
00620 p2=h(j,1)
00630 e2=h(j,2)
00640 if p2<p1 goto 700
00650 if p>p2 goto 670
00660 if p<=p2 goto 720
00670 p1=p2
00680 e1=e2
00690 next j
00700 print "NOT ENOUGH DATA"
00710 goto 930
00720 y=e1+(p-p1)*(e2-e1)/(p2-p1)
00730 e=y*r*r*s*3.1416+u+v
00740 p=(p+101.325)*e/(v+u)
00750 b=0
00760 t1=273
00770 gosub 1920
00780 t2=t1-273
00790 print t2,b
```

```
00800 print #2: t2,b
00810 if t2>=150 goto 930
00820 t1=t1+10
00830 if t2=0 goto 870
00840 if t2=80 goto 900
00850 b=0
00860 goto 770
00870 b1=b
00880 b=0
00890 goto 770
00900 b2=b
00910 b=0
00920 goto 770
00930 n1=(b2-b1)/80
00940 n2=(b-b2)/70
00950 n3=(b-b1)/150
00960 print ""
00970 print "db/dTe 0 to 80 deg C",n1
00980 print "db/dTe 80 to 150 deg C",n2
00990 print "db/dTe 0 to 150 deg C",n3
01000 print "INPUT TEMP COMPENSATION FACTOR"
01010 print #2: ""
01020 print #2: ""
01030 print #2: ""
01040 print #2: ""
01050 print #2: "db/dTe 0 to 80 deg C  =",n1
01060 print #2: "db/dTe 80 to 150 deg C  =",n2
01070 print #2: "db/dte 0 to 150 deg C  =",n3
01080 print #2: ""
01090 print #2: ""
01100 input n
01110 print #2: "TEMP CORRECTION FACTOR mm/deg C  =",n
01120 print #2: ""
01130 print #2: ""
01140 print #2: ""
```

```
01150 print #2: " "
01160 t1=300
01170 gosub 1920
01180 t=t+75
01190 t1=273
01200 dim c (8,9)
01210 mat c=zer
01220 for i=1 to 8
01230 for j=2 to 9
01240 b1=b+n*(t1-300)
01250 p1=0
01260 e1=0
01270 for k=1 to 40
01280 p2=h(k,1)
01290 e2=h(k,2)
01300 if e2<e1 goto 1390
01310 if b1>e2 goto 1340
01320 if e2=0 goto 1340
01330 if b1<=e2 goto1370
01340 e1=e2
01350 p1=p2
01360 next k
01370 z=p1+(b1-e1)*(p2-p1)/(e2-e1)
01380 goto 1410
01390 print "NOT ENOUGH PRESSURE-EXTENSION DATA"
01400 stop
01410 z1=(p*t*t1*(v+u))/(300*(v*t1+t*(u+b1*r*r*s*3.1416)))
01420 z2=z1-z-101.325
01430 print #3: using "-#####  -#####.####",t1-273,z2
01440 t1=t1+20
01450 c(i,j)=z2
01460 next j
01470 c(i,1)=t-273
01480 t1=273
01490 t=t-25
```

```
01500 next i
01510 print "     Ts        Te=0, Te=20, Te=40, Te=60, Te=80,Te=100,Te=120,Te=140"
01520 print " "
01530 mat print using "-###.#,   -###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#",c
01540 print #2: " "
01550 print #2: " "
01560 print #2: " "
01570 print #2: "     Ts        Te=0, Te=20, Te=40, Te=60, Te=80,Te=100,Te=120,Te=140"
01580 print #2: " "
01590 mat print #2: using "-###.#,   -###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#",c
01600 stop
01610 '
01620 '
01630 '
01640 '
01650 rem PRESSURE CALC. SUBROUTINE FOLLOWS
01660 d=b*r*r*s*3.1416
01670 a=t*t1*(v+u+d)
01680 c=v*t1+t*(u+d)
01690 f=a/c
01700 m=p*(v+u)*f/(300*(v+u+d))
01710 w=m-o-101.325
01720 p1=0
01730 e1=0
01740 for j=1 to 40
01750 p2=h(j,1)
01760 e2=h(j,2)
01770 if e2<e1 goto 1860
01780 if b>e2 goto 1810
01790 if e2=0 goto1810
01800 if h<=e2 goto 1840
01810 e1=e2
01820 p1=p2
01830 next j
01840 z=p1+(b-e1)*(p2-p1)/(e2-e1)
```

```
01850 return
01860 print "NO MORE DATA FOR SUBROUTINE"
01870 goto 930
01880 ,
01890 ,
01900 ,
01910 ,
01920 rem PRESSURE COMPARISON SUBROUTINE FOLLOWS
01930 gosub 1650
01940 if z=w goto 2100
01950 if z>w goto 1980
01960 b=b+0.1
01970 goto 1930
01980 b=b-0.01
01990 if b<0 goto 2040
02000 gosub 1650
02010 if z<w goto 2050
02020 if z=w goto 2100
02030 if z>w goto 1980
02040 b=0
02050 b=b+0.001
02060 gosub 1650
02070 if z<w goto 2050
02080 if z=w goto 2100
02090 if z>w goto 2100
02100 b=int(b*10^3+0.5)/10^3
02110 return
02120 end
```

APPENDIX 4

FILE voutput

The data shown is for experimental F.F.D. number 31.

DATE OF COMPUTATION   07/23/81

PHIAL VOL mm^3   = 500
CAPSULE RAD. mm   = 9
FILL PRESSURE KPa GAUGE   = 164.675
DEAD VOLUME mm^3   = 60
START PRESSURE KPa   = 0
OPENING TEMP. (Ts), DEG C   = 325

Te deg C	TOTAL EXT.
0	0.689
10	0.699
20	0.707
30	0.716
40	0.724
50	0.732
60	0.74
70	0.747
80	0.754
90	0.761
100	0.768
110	0.774
120	0.781
130	0.787
140	0.793
150	0.798

dh/dTe 0 to 80 deg C   = 8.125 E-4
dh/dTe 80 to 150 deg C   = 6.28571 E-4

db/dte 0 to 150 deg C   =   7.26667 E-4

TEMP CORRECTION FACTOR mm/deg C   =   0.0007

Ts	Te=0,	Te=20,	Te=40,	Te=60,	Te=80,	Te=100,	Te=120,	Te=140
400.0,	25.2,	29.0,	31.9,	34.0,	35.4,	36.2,	36.5,	36.3
375.0,	16.1,	19.4,	21.9,	23.6,	24.7,	25.1,	25.1,	24.5
350.0,	6.7,	9.5,	11.6,	12.9,	13.6,	13.7,	13.3,	12.5
325.0,	-3.1,	-0.7,	1.0,	1.9,	2.2,	1.9,	1.2,	0.1
300.0,	-13.2,	-11.2,	-10.0,	-9.5,	-9.6,	-10.2,	-11.2,	-12.7
275.0,	-23.6,	-22.1,	-21.3,	-21.2,	-21.7,	-22.6,	-24.0,	-25.7
250.0,	-34.4,	-33.3,	-33.0,	-33.3,	-34.1,	-35.4,	-37.1,	-39.1
225.0,	-45.5,	-44.9,	-45.1,	-45.7,	-46.9,	-48.6,	-50.6,	-53.0

Flame Detection Methods Needing Electricity Supply

Table 1

TYPE	INPUT TO SENSOR	COMMENTS	REFERENCES
Flame Conductivity	Electrical conductivity of flame	Electrical leakage on insulators can simulate a flame	1, 2, 4, 8, 9, 10
Flame Rectification	Flame directional conductivity	Detection of rectification effect eliminates problems due to electrical leakage	8, 9, 10, 11
Flame Voltage	Voltage generated by flame (can be up to 2 volts)	Very low current output necessitates high imput impedance detector	8
Infra Red	Infra red radiation from flame	Can be affected by background radiation from hot surroundings. This can be overcome by making the detector system responsive to radiation with a flicker superimposed on it.	8, 10, 11
Ultra Violet	U.V. light from flame	Detector must be kept cool and shielded from sunlight and other sources of U.V. such as spark igniters	8, 10, 11

Table 1 (continued)

TYPE	INPUT TO SENSOR	COMMENTS	REFERENCES
Inverted Flame	Visible light from flame	Stream of gas injected into blue flame to increase visible light output. Light detected by a photo conductor	8
Partial Reflection	Light reflected from flame	Light beam strikes flame. Photocell picks up reflected light	8
Thermistor	Flame heat	Thermistors not available for high temperatures (300 °C max)	8
Salt Cell	Flame heat	When salt melts its electrical resistance drops. This could possibly control a magnetic valve without the need for an amplifier	8
Thermocouple Switch	Flame heat	Thermocouple current operates electromagnetic switch	10
Mercury Flame Switch	Flame heat	Thermal element similar to mercury F.F.D. operates a microswitch	15

FLAME DETECTION METHODS PRODUCING MECHANICAL MOTION

Table 2

TYPE	OUTPUT FROM SENSOR	DISADVANTAGES	REFERENCES
Mercury	Mechanical Motion	a) Possible mercury vapour hazard b) Hot mercury dissolves metal walls of device redepositing it elsewhere causing blockage	2, 4, 16
Thermoelectric	Electric current. Sufficient current to operate electromagnet which can hold spring loaded valve open	a) Insufficient energy to open valve. This must be done manually. b) Thermocouple life quite short	1, 2, 3, 4, 9, 10
Bimetallic Strip	Mechanical Motion	a) Bimetallic sensor can warp after long use, holding valve open b) Valve must be connected by inflexible mechanical linkage to sensor c) Exposed mechanism means that it is not tamperproof	1, 2, 4, 9
Bimetallic Rod and Tube	Mechanical Motion	a) Small movements generated	1, 2

Table 2 (continued)

TYPE	OUTPUT FROM SENSOR	DISADVANTAGES	REFERENCES
Unimetallic	Mechanical Motion	a) Very small movements available b) Inflexible linkage between sensor and valve	2, 9
Porous Plug	Pressure drop across plug. This could be used to operate a relay valve.	a) Expensive due to need for complex relay valve b) Pressure changes developed small 6.75 mb on prototype. c) Blockage of porous plug could simulate a flame condition.	8
Curie Temperature	Mechanical Motion	a) Difficult to construct. b) Forces generated quite low.	8

Table 3

MERCURY F.F.D. FIELD FAILURE DATA

FAILURE MODE	FIELD FAILURES IN 10 YEAR LIFE
Swarf causing valve leakage	0.7%
Capsule cracking	2.1%
Capsule-boss weld cracking	0.3%
Capsule permanent set	2.1%
Capillary	0.4%
Blockage	4.0%
Phial cracking	5.0%
Phial closure weld failure	0.4%
TOTAL	15.0%

NOTES

1) U.K. population of mercury F.F.D.'s
    2,156,000 in December 1977

2) Yearly replacement rate = 1.5% (approximately 32,000)

3) Taken from (28)

Table 4

FAILURES EXPERIENCED IN CYCLIC TESTING OF MERCURY VAPOUR FLAME FAILURE DEVICES

TYPE	NUMBER TESTED	NO. OF FAILURES	NO. OF CYCLES AT FAILURE	TYPE OF FAILURE	CAUSE OF FAILURE
Mercury Vapour	230	19	0	⎫	⎫
			0	⎪	⎪
			0	⎬ (Leaking (unsafe)	⎬ (Swarf on valve pad
			0	⎪	⎪
			0	⎭	⎭
			2020		
			2040		
			4040		
			5500		
			6000	Closed (safe)	Bellows rupture
			6000	Closed (safe)	Bellows rupture
			6075	Leaking (unsafe)	Swarf on valve pad
			6315	Closed (safe)	Bellows rupture
			6390	Leaking (unsafe)	"
			6800	Closed (safe)	"
			7300	"	"
			7600	"	"
			7680	Leaking (unsafe)	"
			8750	Closed (safe)	"

Taken from Wharf (29)

Table 5

SUMMARY OF BS 5258 F.F.D. REQUIREMENTS

BS 5258 PART NUMBER	APPLIANCE	F.F.D. REQUIRED?	MAX. OPENING TIME	MAX. CLOSING TIME
1	Boiler	yes	40 seconds	60 seconds
	Circulator	yes	90 seconds	90 seconds
2	Cookers	yes	90 seconds	90 seconds
3	Drying Cabinet	yes (except when flames can be seen with doors closed)	90 seconds	90 seconds
4	Ducted air heaters	yes	40 seconds	60 seconds
5	Gas fires	Only when gas supply to main burner is turned on automatically	90 seconds	3 minutes

Table 5 (continued)

BS 5258 PART NUMBER	APPLIANCE	F.F.D. REQUIRED?		MAX. OPENING TIME	MAX. CLOSING TIME
6	Refrigerators and food freezers	Only when 3rd family gas is used		90 seconds	90 seconds
7	Storage water heater	yes	<8 kw heat input	90 seconds	90 seconds
			>8 kw heat input	40 seconds	60 seconds
8	Combined appliances	Necessary in boiler	Boiler	40 seconds	60 seconds
			Circulator	90 seconds	90 seconds
	Gas fire/ back boiler	Only necessary on gas fire if turned on automatically	Gas fire	90 seconds	3 minutes

Table 5 (continued)

BS 5258 PART NUMBER	APPLIANCE	F.F.D. REQUIRED?	MAX. OPENING TIME	MAX. CLOSING TIME
10	Non catalytic flueless space heater	yes	90 seconds	90 seconds
11	Catalytic flueless space heater	Not applicable	----	----
12	Decorative log fires	Only necessary if turned on automatically, or if greater than 7.3 kw heat input	90 seconds	2 minutes

Table 6

DIFFUSION CONSTANTS

TEMP. °C	MATERIAL COMBINATION	D cm²/sec	REF
1100 (800)	O^{2-} in Cr_2O_3	10^{-15} (10^{-19})	56
1100	Cr^{3+} in Cr_2O_3	10^{-11}	57
800	Oxygen in Fe $(\alpha + \delta)$	8.3×10^{-7}	52
800	Nitrogen in Fe $(\alpha + \delta)$	1.36×10^{-6}	52
1100	Nitrogen in Fe (γ)	4.7×10^{-7}	52

COMPARISON OF DIAPHRAGM MATERIALS

Table 7

MATERIALS	2% YIELD STRESS (σ_y) MPa	ELASTIC MODULUS (E) GPa	RATIO $\sigma_y/E \times 10^3$
Beryllium—copper*	1066	127.5	8.4
Monel K-500*	600	165	3.6
Phosphor bronze ½H	386	107	3.6
H	579		5.4
Inconel X 750*	900	221	4.1
17-7 PH*	1275	195	6.5
¼H	520	200	2.6
302 ½H	800	200	4
H	1100	200	5.5

* Indicates precipitation hardening.

Table 8

PROPERTIES OF FUEL GASES

FUEL GAS	RELATIVE DENSITY	WOBBE INDEX (S.I.)
Normal U.K. town Gas	0.47	27.2
U.K. natural gas	0.586	50.7
Propane	1.552	75.4
Butane	2.006	85.9
Nitrogen*	0.967	----

* Included for flow measurement purposes.

Figure 1

STAINLESS STEEL SHEATH

COPPER TUBE AND WIRE

COLD JCT

HOT JCT

CONSTANTAN WIRE

GLASS FIBRE

THERMOCOUPLE

THERMOCOUPLE LEAD

MAGNET ASSEMLY

INLET

VALVE

TO PILOT

RESET BUTTON

VALVE
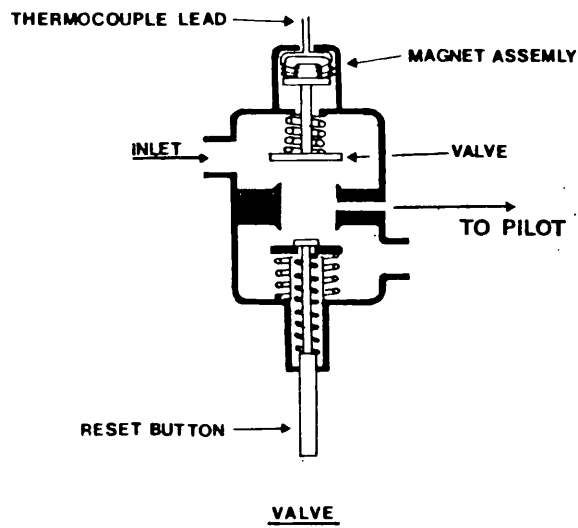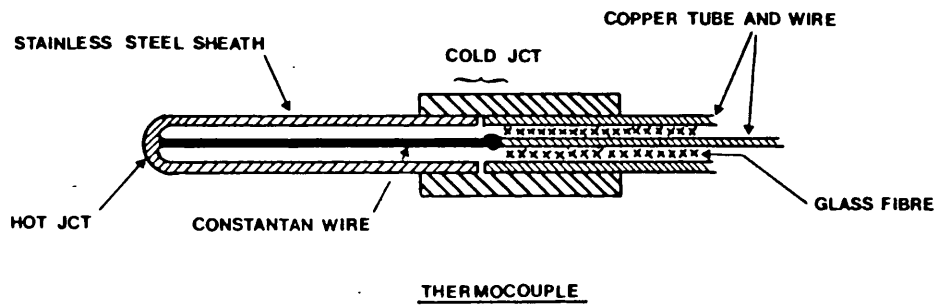
Schematic diagram of a thermoelectric flame failure device.

Figure 2

A typical thermoelectric flame failure device.

Figure 3

MERCURY

PHIAL

PILOT

DIAPHRAGM
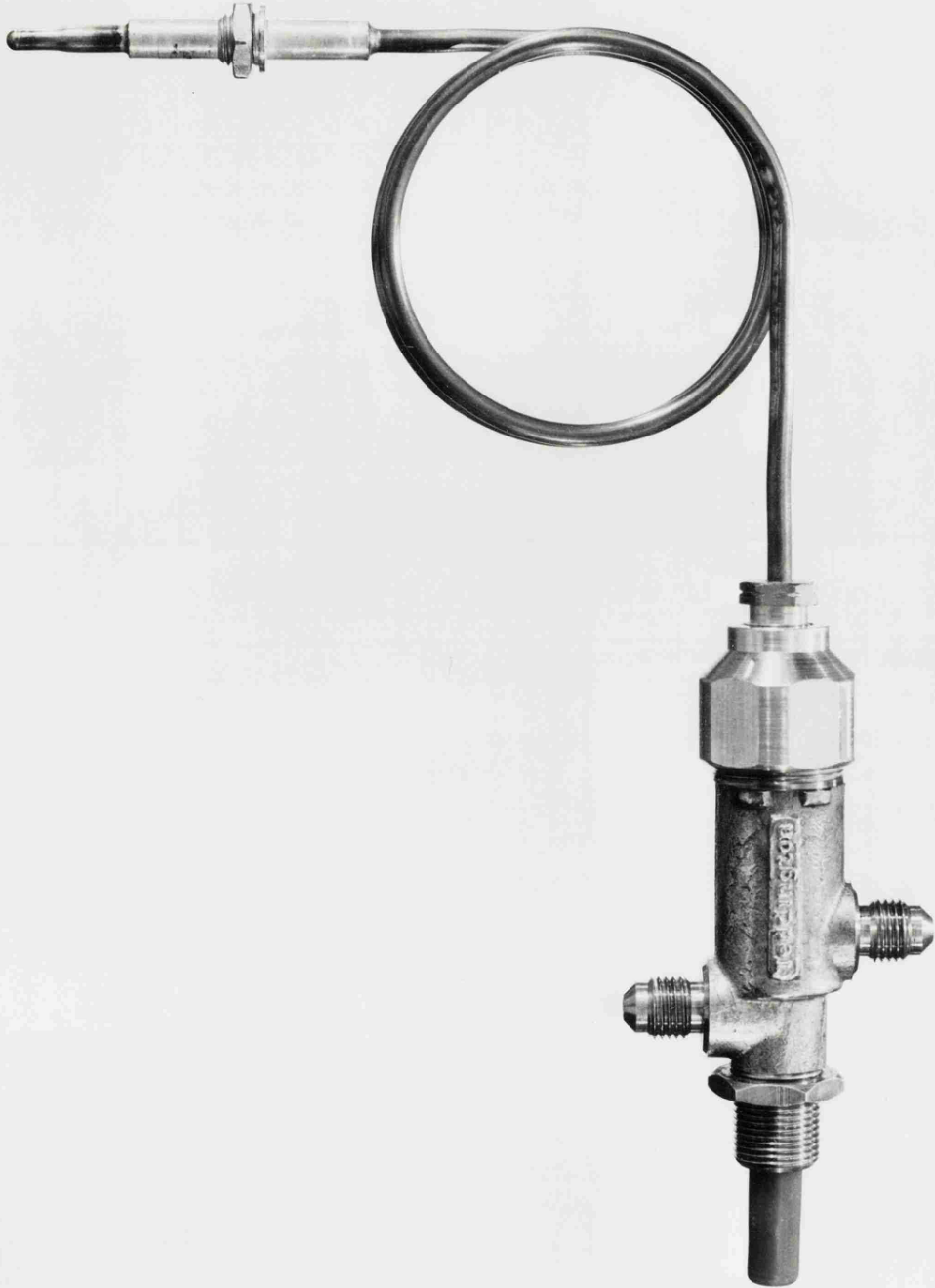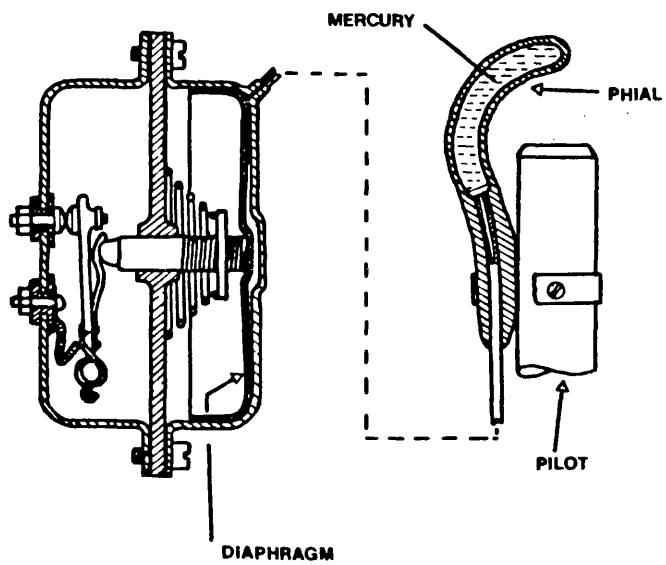
Cobb flame switch.
Taken from U.S. patent 2640313 (15).

Figure 4

PHIAL

FILLER WIRE

CAPSULE

LEVERS
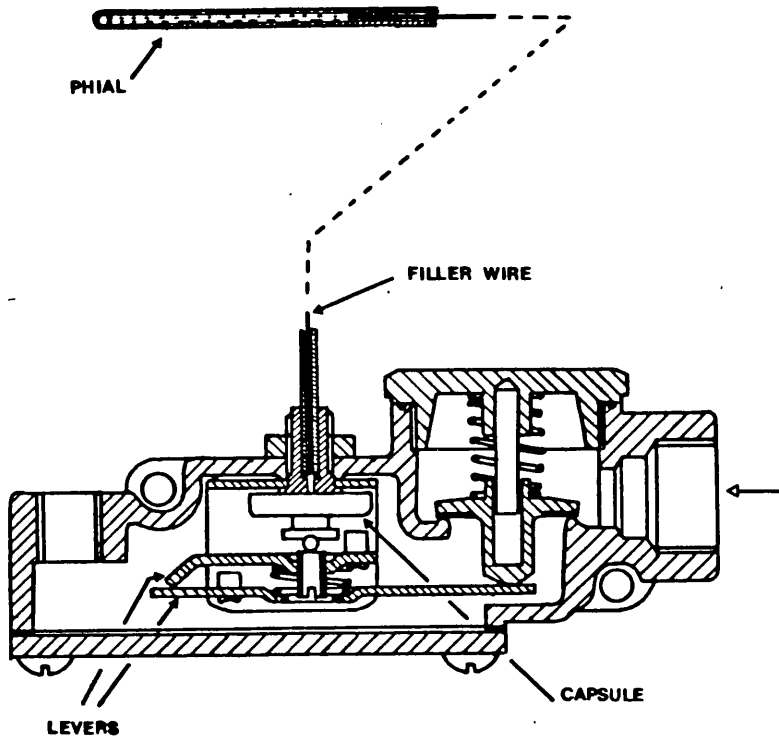
Weber flame failure device.
Taken from U.S. patent 3213922 (16).

Figure 5
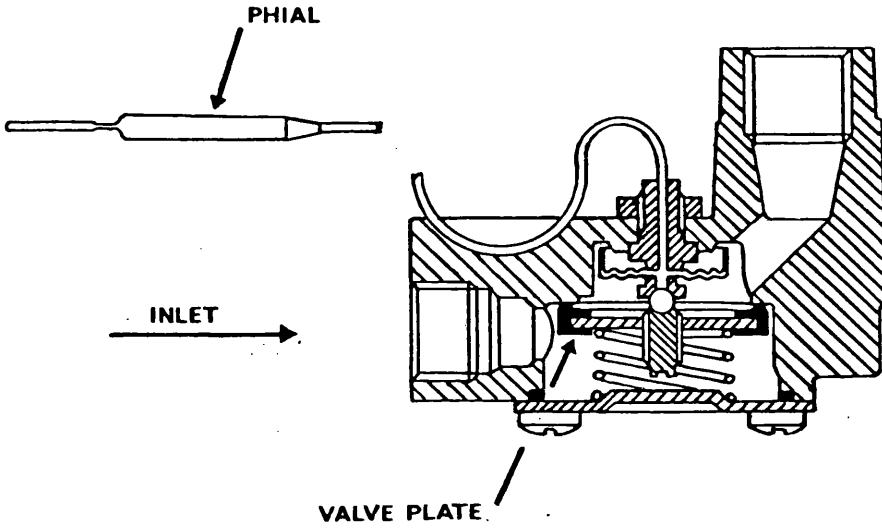
Harper Wyman 5920 mercury flame failure device.

Figure 6

A Harper Wyman type 5920 mercury flame failure device.
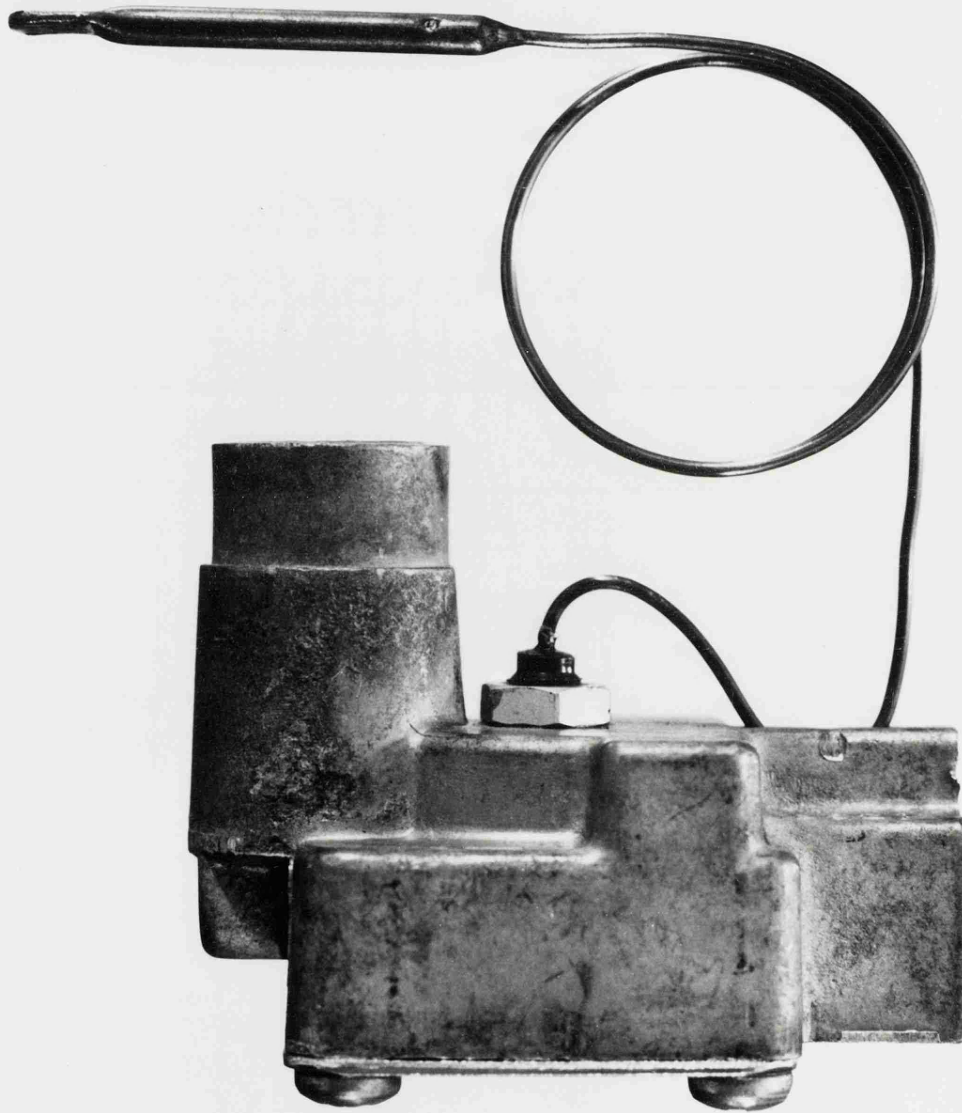
Figure 7

Bypass type oven control system.

Figure 8

BURNER

SPARK IGNITER

PILOT

TIMER VALVE

F.F.D.

THERMOSTAT

L

N
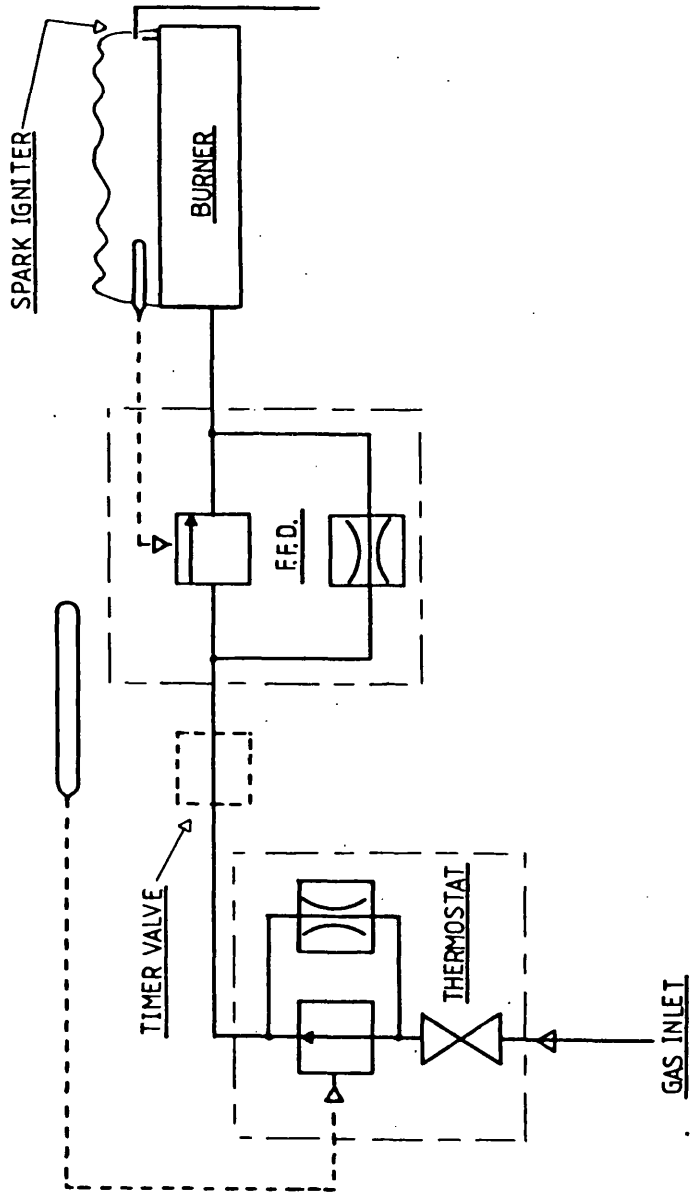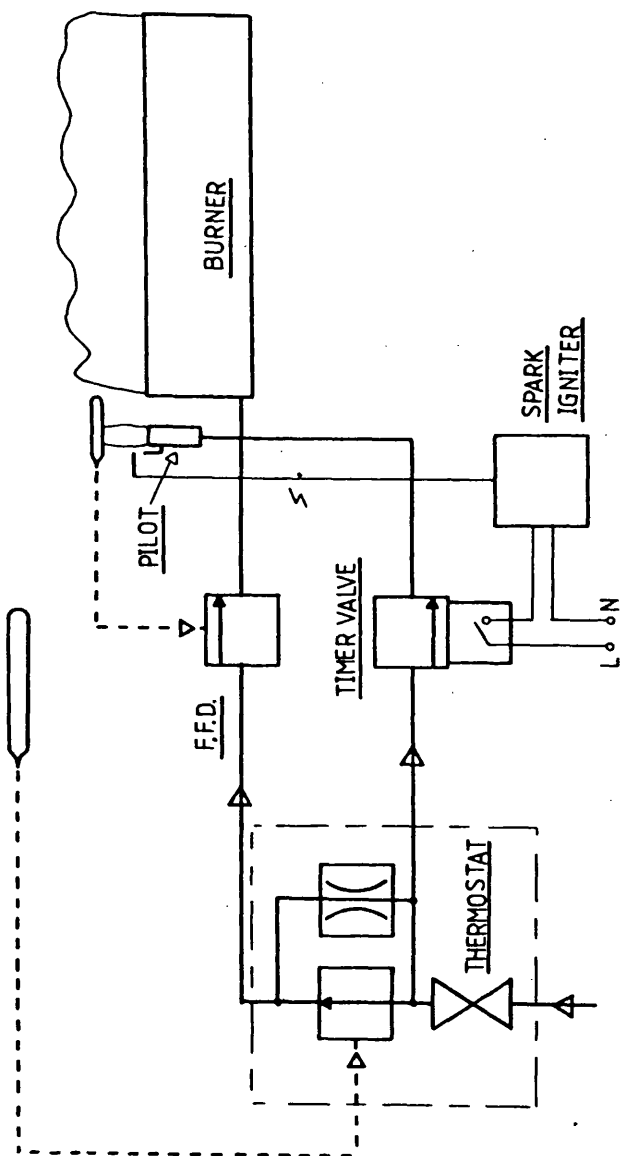
Non-bypass type oven control system.
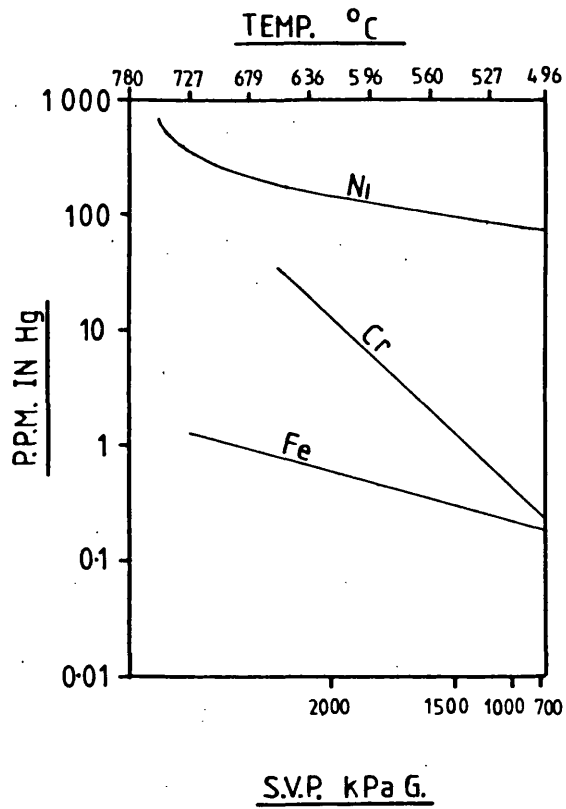
Figure 9

Solubilities of some metals in mercury. Taken from Weeks (30).

Figure 10

Condition of the inside of a mercury F.F.D. phial after
3388 hours continuous running. The lighter regions are
where erosion and deposition have occurred.

Figure 11
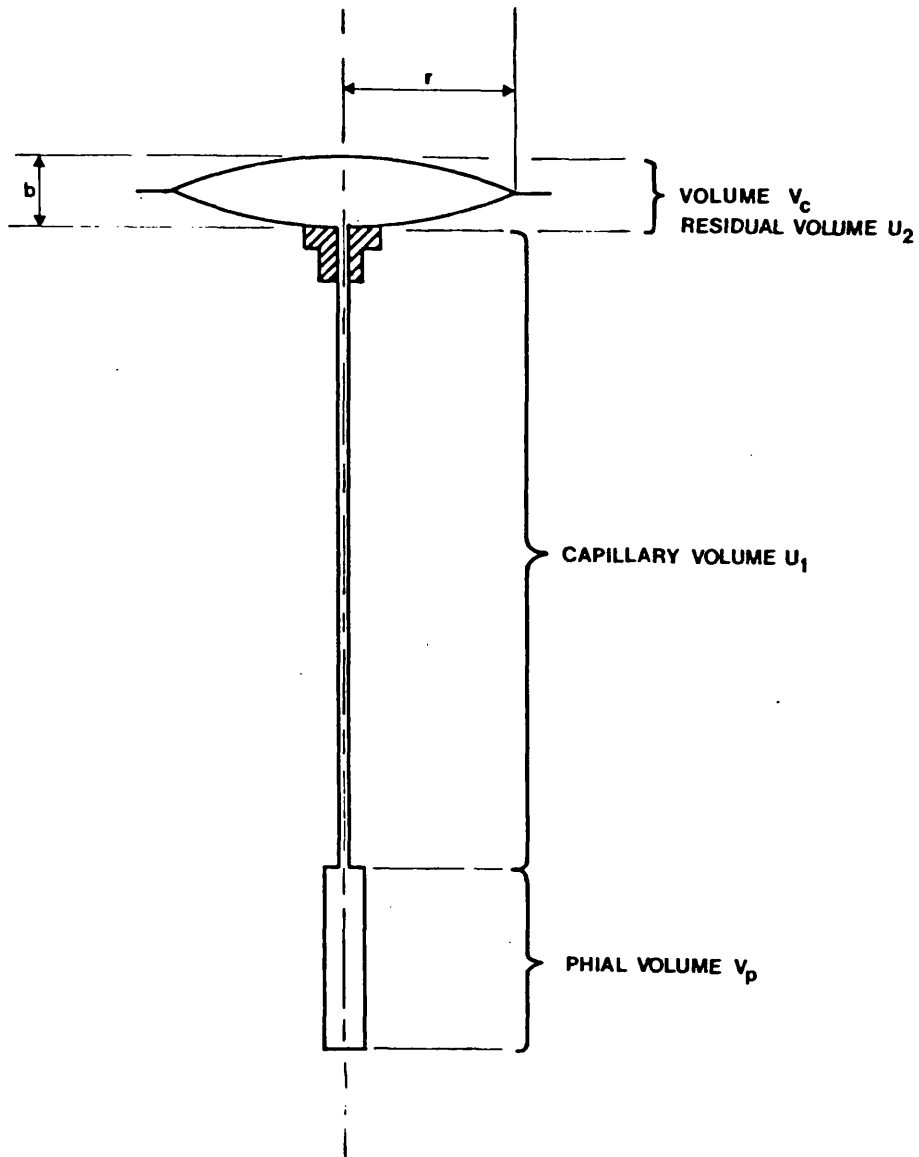
Model of a gas filled thermal system.

Total dead volume $= U_1 + U_2 = U$

Figure 12

1 — N_2 – Fe
2 — H_2 – Fe
3 — H_2 – 18-8 STEEL
4 — H_2 – 14% Cr STEEL
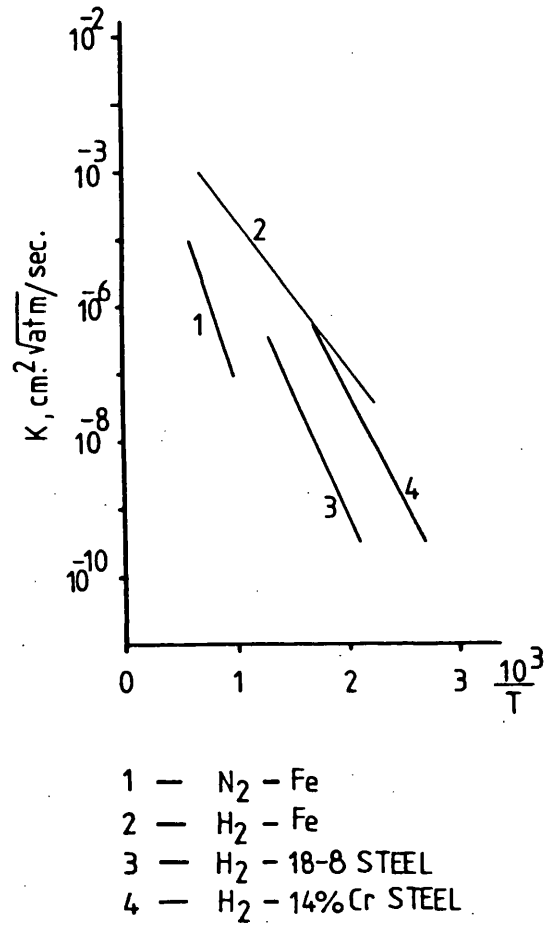
Permeation constants for various gas – metal combinations.
Taken from Redhead et al (54).

Figure 13
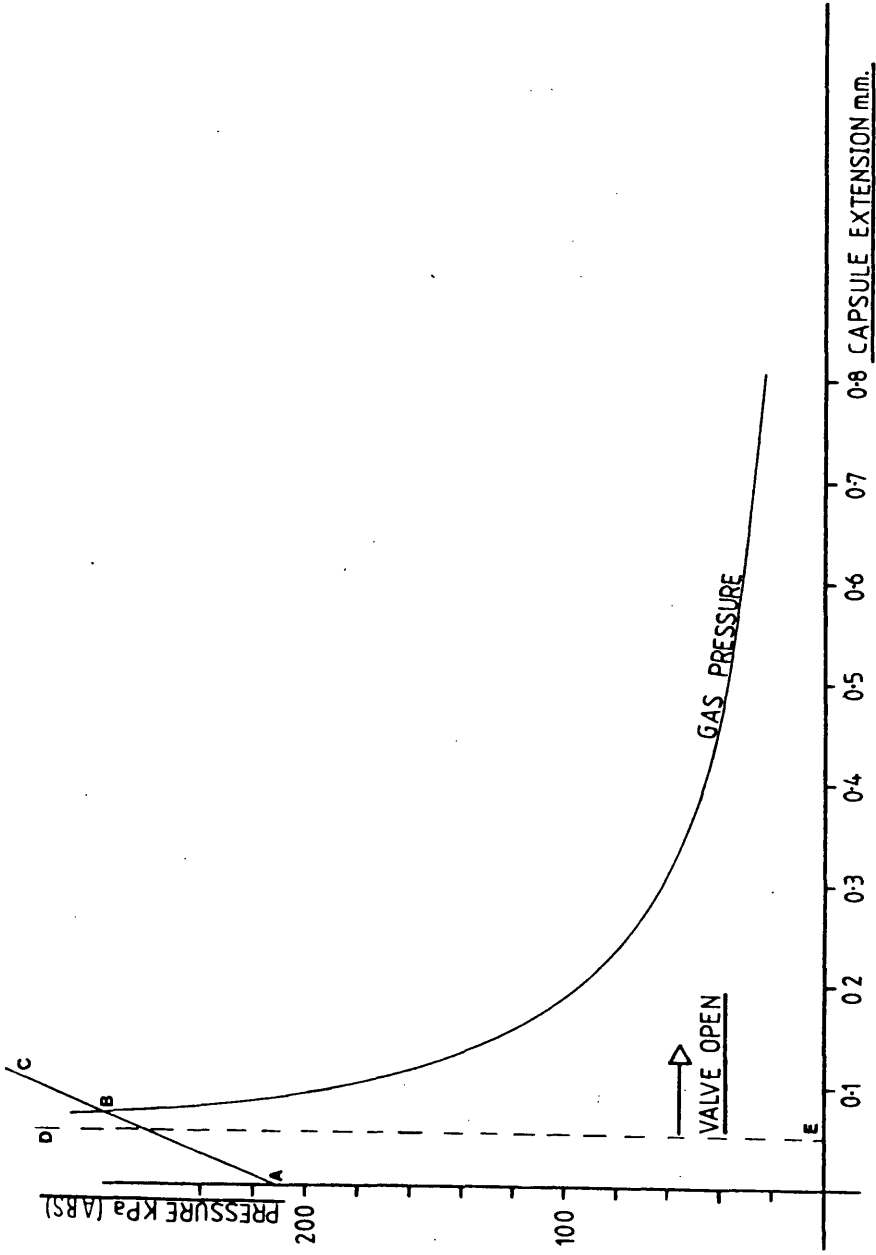
The 27 °C pressure variation of gas which permeated to an equilibrium of 79 kPa at 700 °C in a Harper Wyman type 5920 mercury F.F.D.

Figure 14
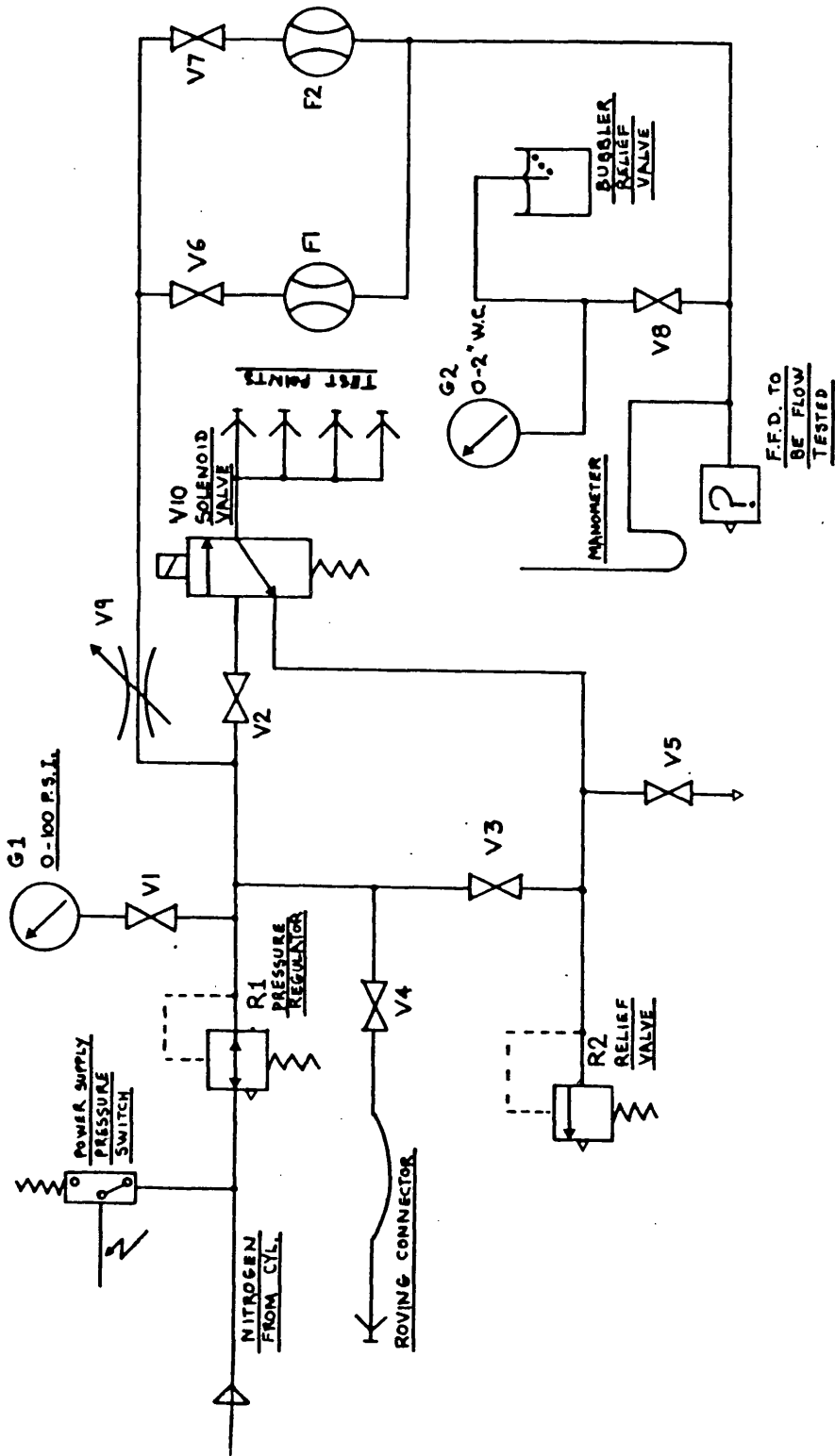
The multi-purpose test rig.

Figure 15

The multi-purpose test rig.

The tube furnace used for thermal system testing can

be seen to the far right of the photograph.

Figure 16
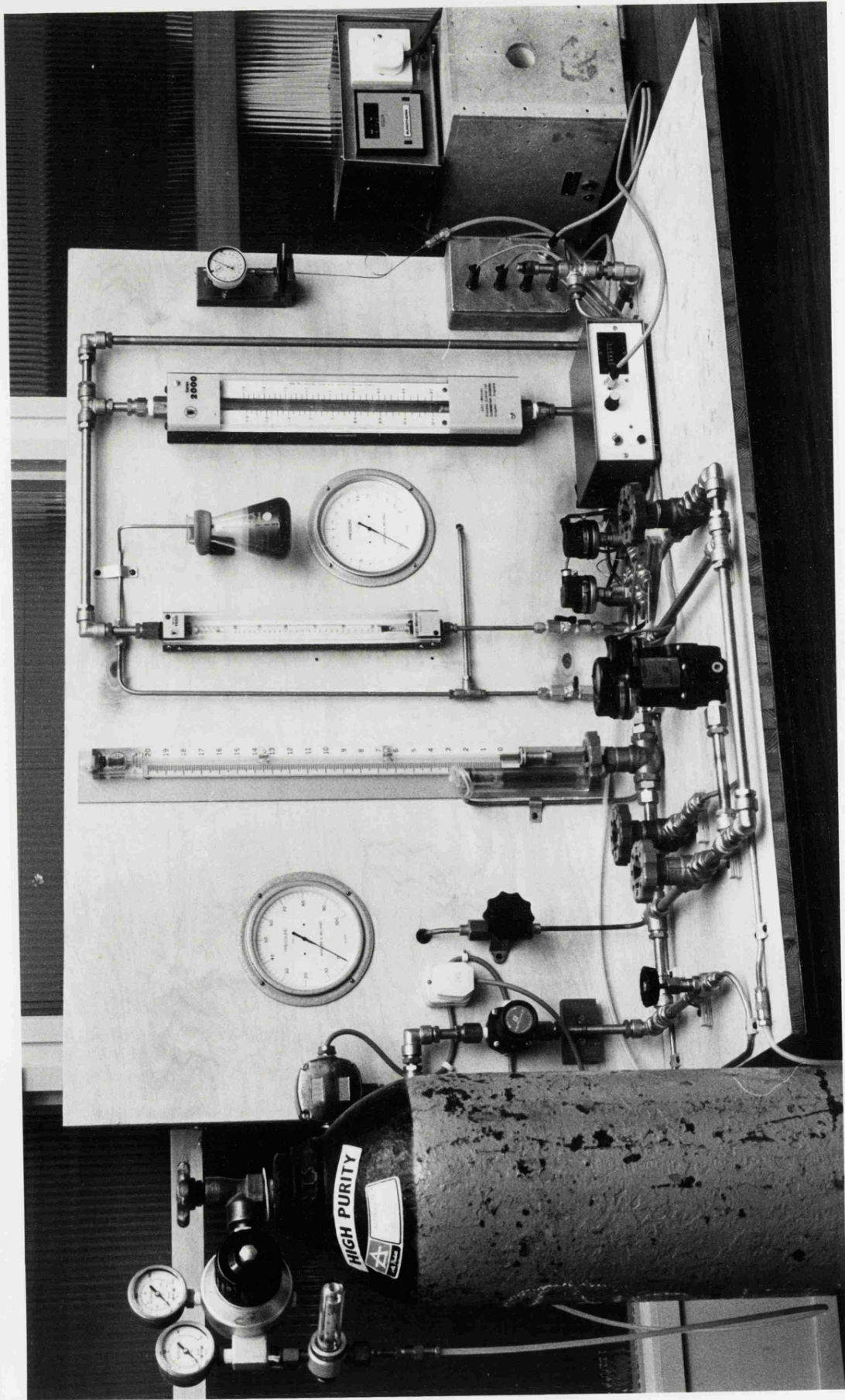
VALVE BODY PRESSURE DROP
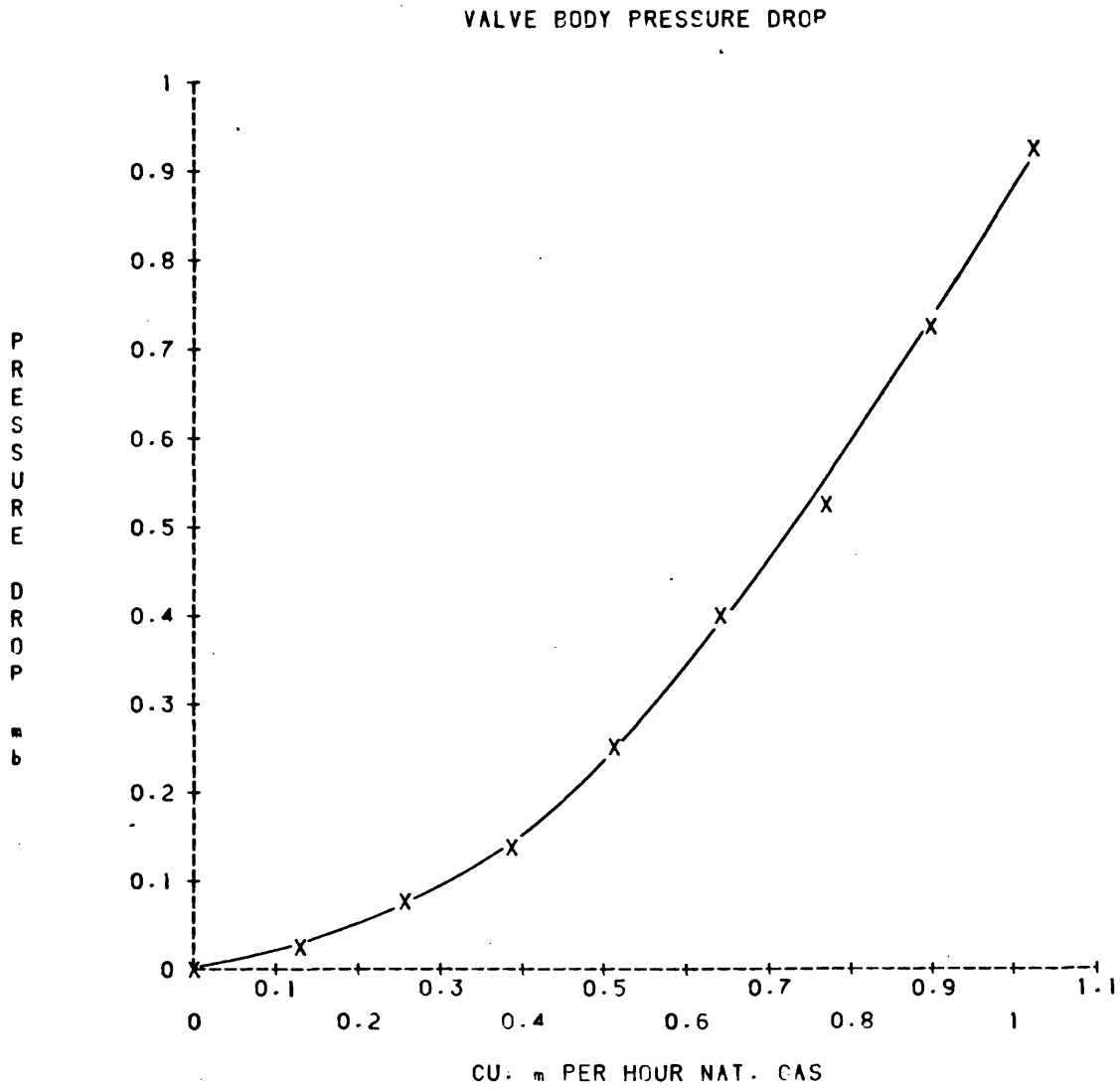
The pressure drop at 0.75 mm valve lift for a ¼" B.S.P. Harper Wyman F.F.D. body.

Figure 17

VALVE PLATE PRESSURE DROP
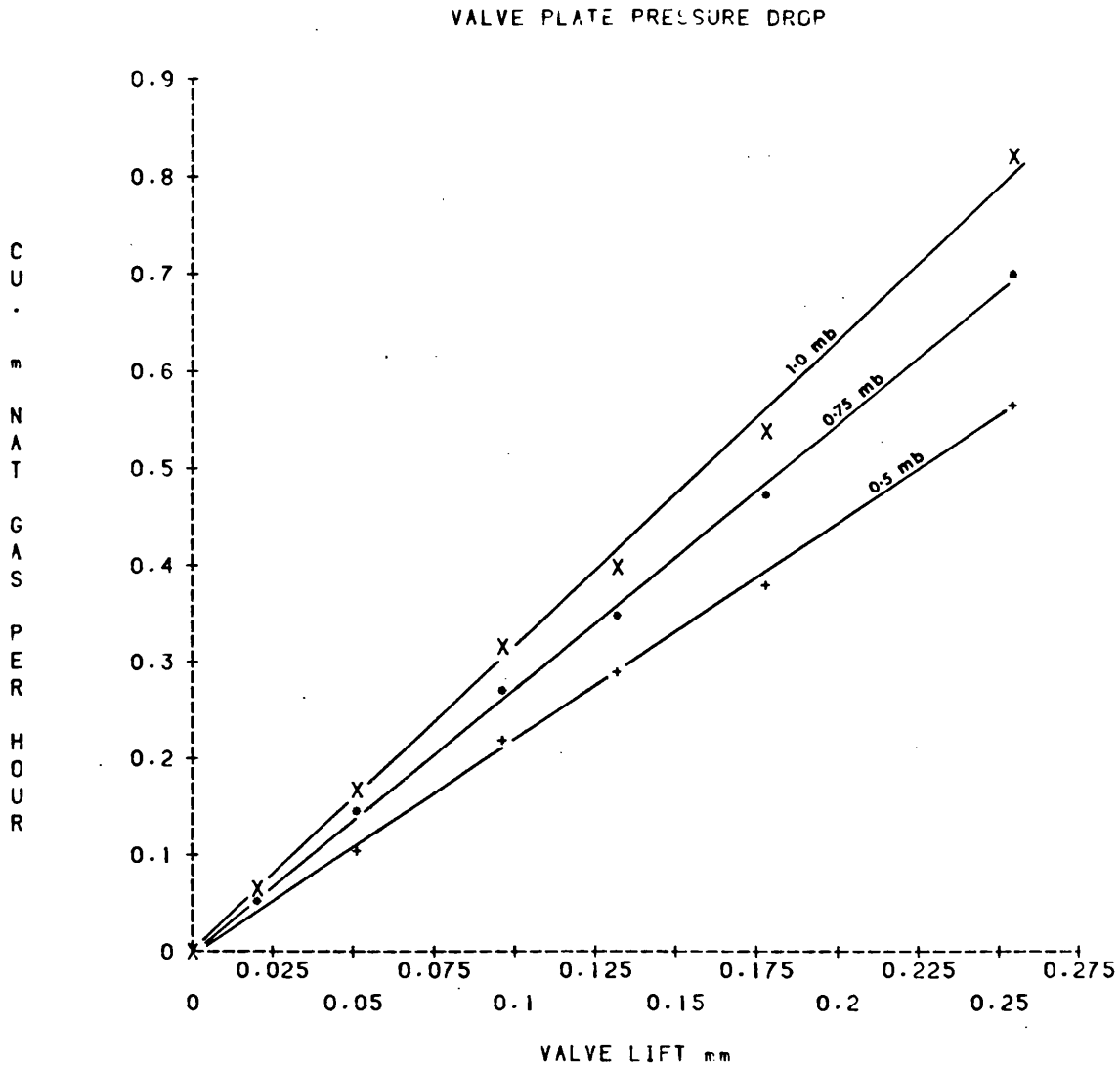
The relationship between gas flow and valve lift at 1.0 mb, 0.75 mb and 0.5 mb pressure drop, for the valve plate and seat shown in fig. 18.

Figure 18

silicone rubber seal

·89 mm

·25 mm rad.

25 mm

30°

A

22·5 mm
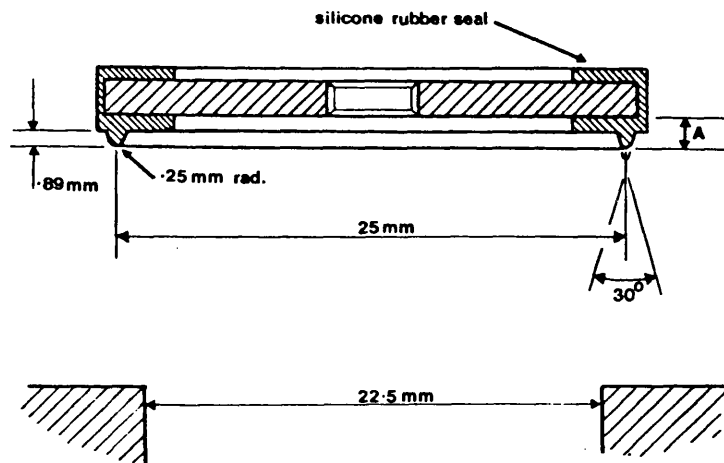
Standard valve plate and seat dimensions.

Figure 19
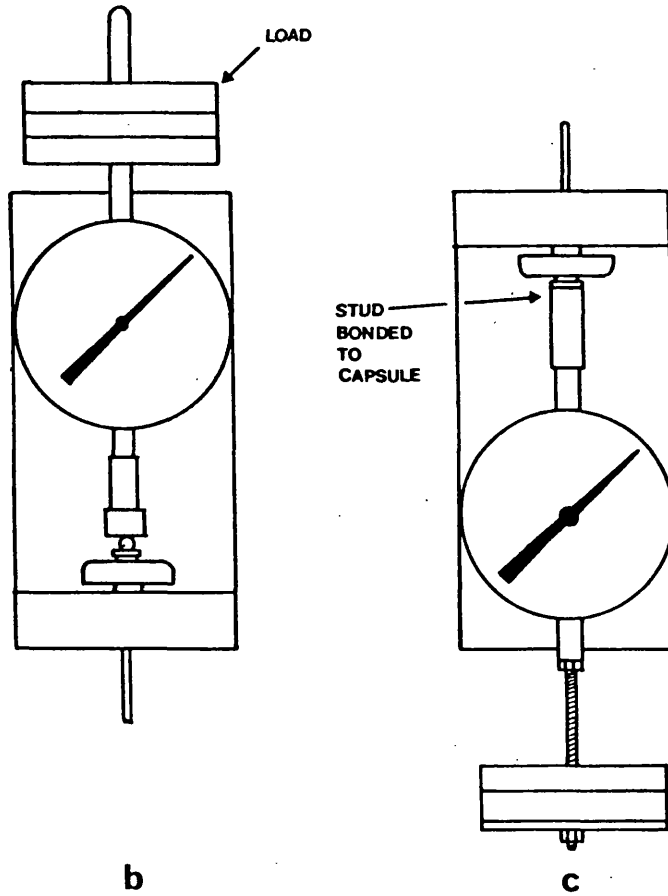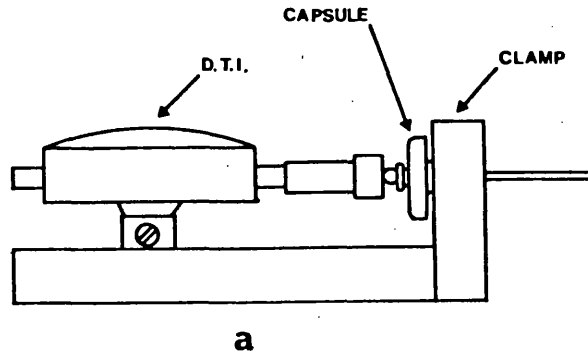
The apparatus for measuring capsule extension
a) Under zero load
b) Under positive loads
c) Under negative loads.

Figure 20

PERFORMANCE OF CAPSULE NO.7

X = 2·28 x 10⁻⁹ m/Pa
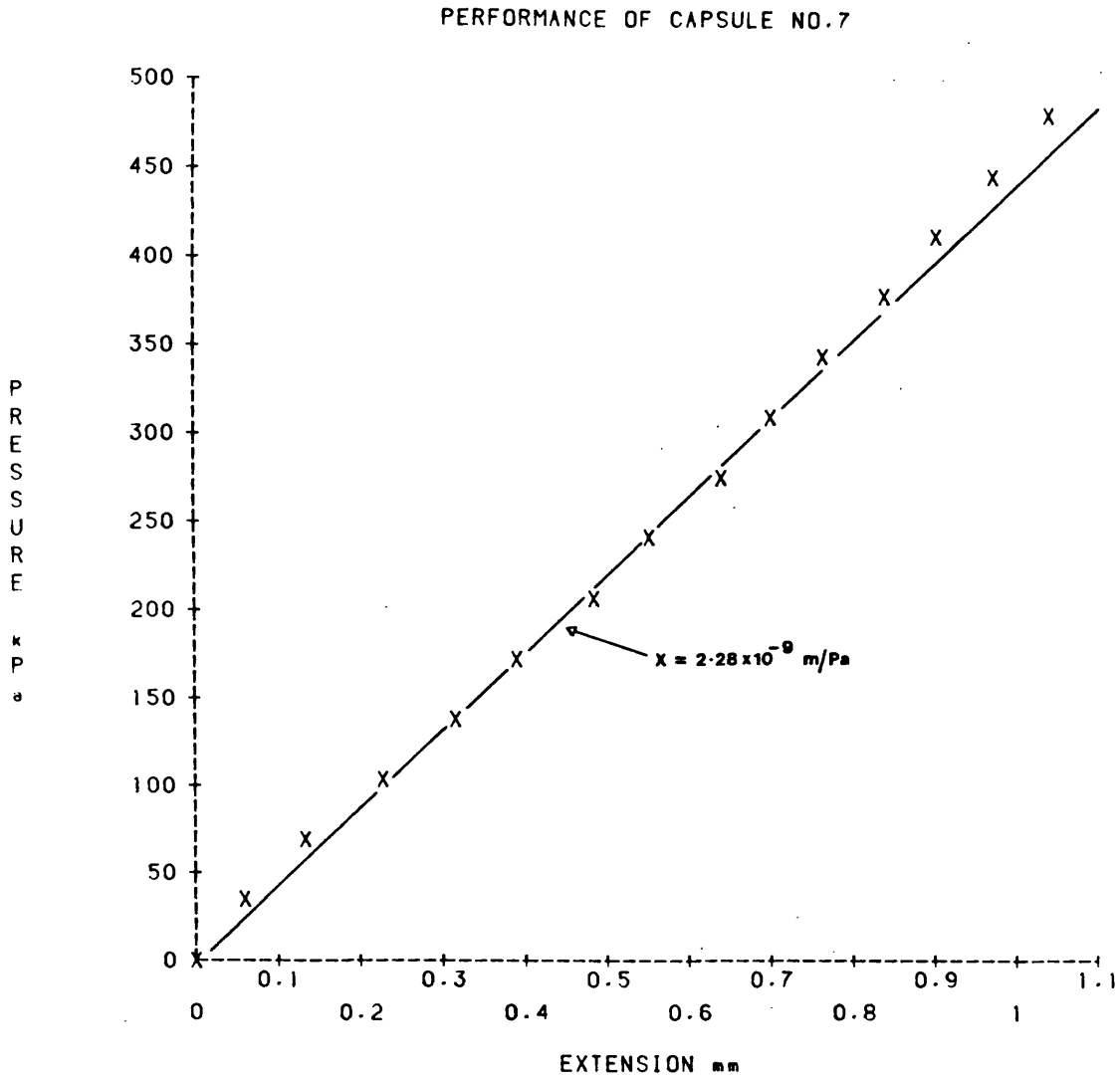
Pressure-extension performance of the capsule used in thermal system number 7.

Figure 21

PERFORMANCE OF CAPSULE NO.4
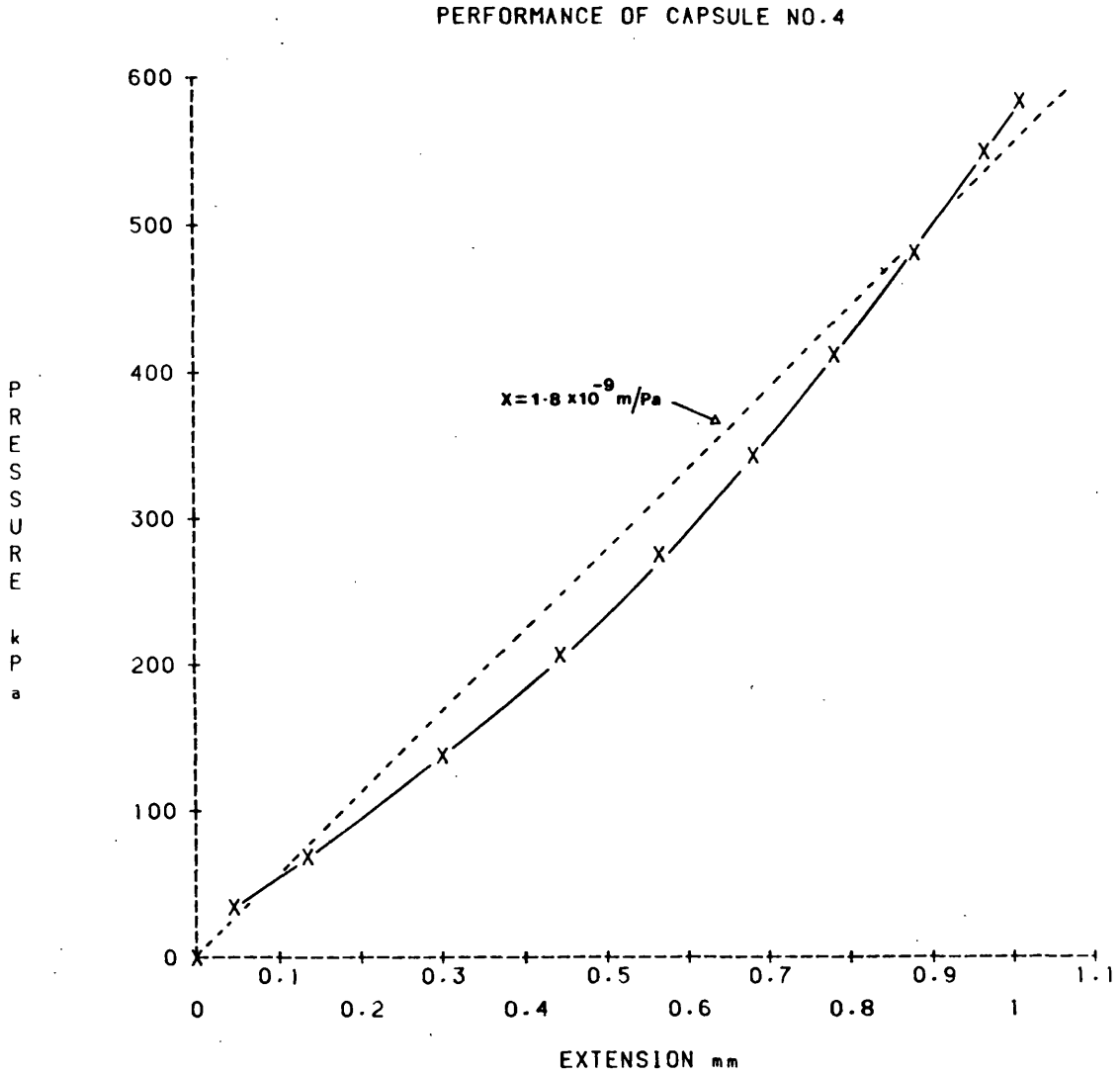
Pressure-extension performance of the capsule used in
thermal system number 4.

Figure 22

PERFORMANCE OF CAPSULE NO. 31
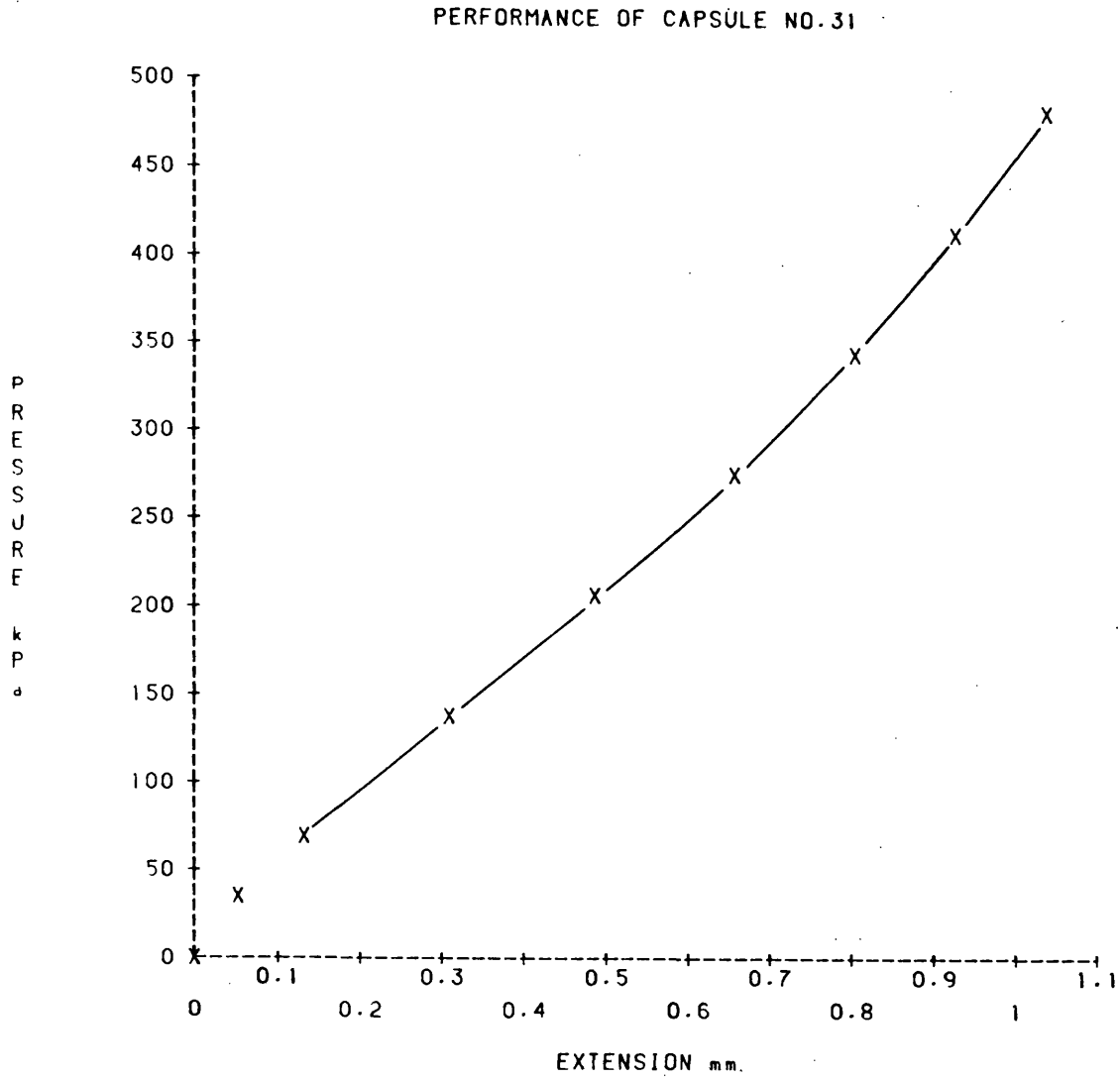
Pressure-extension performance of the capsule used in thermal system number 31.

Figure 23

CORRUG.
DEPTH
~0·23mm

18·8mm

TOP BOSS

DIAPHRAGMS 0·127mm THICK

PROJECTION WELD
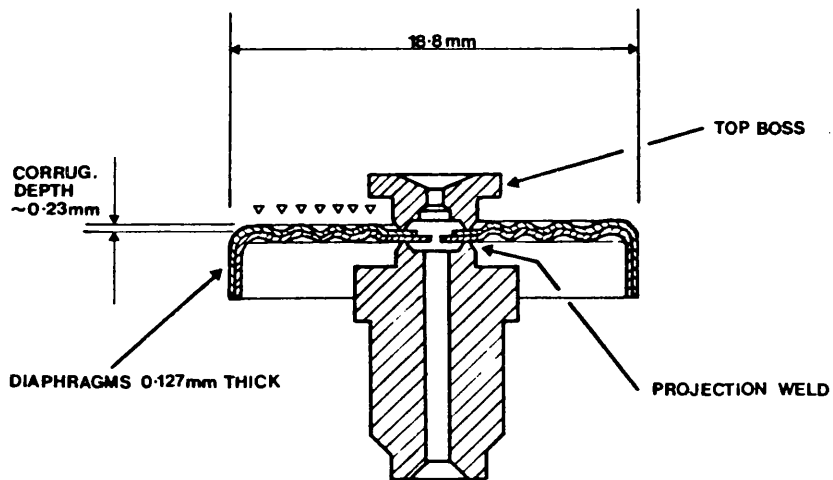
Standard 18 mm diameter Harper Wyman capsule.

∇ indicates the positions where diaphragm thickness
measurements were made (see section 7.7).

Figure 24
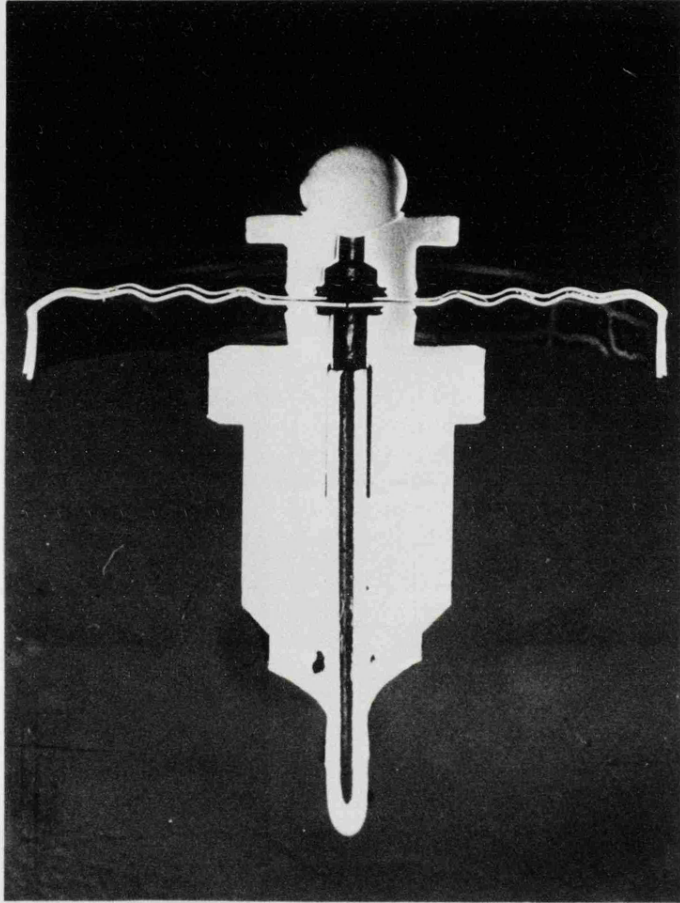
Section through a standard Harper Wyman 18 mm diameter
mercury F.F.D. capsule.

Figure 25

H.W. 18mm DIA. CAPSULE HYSTERESIS
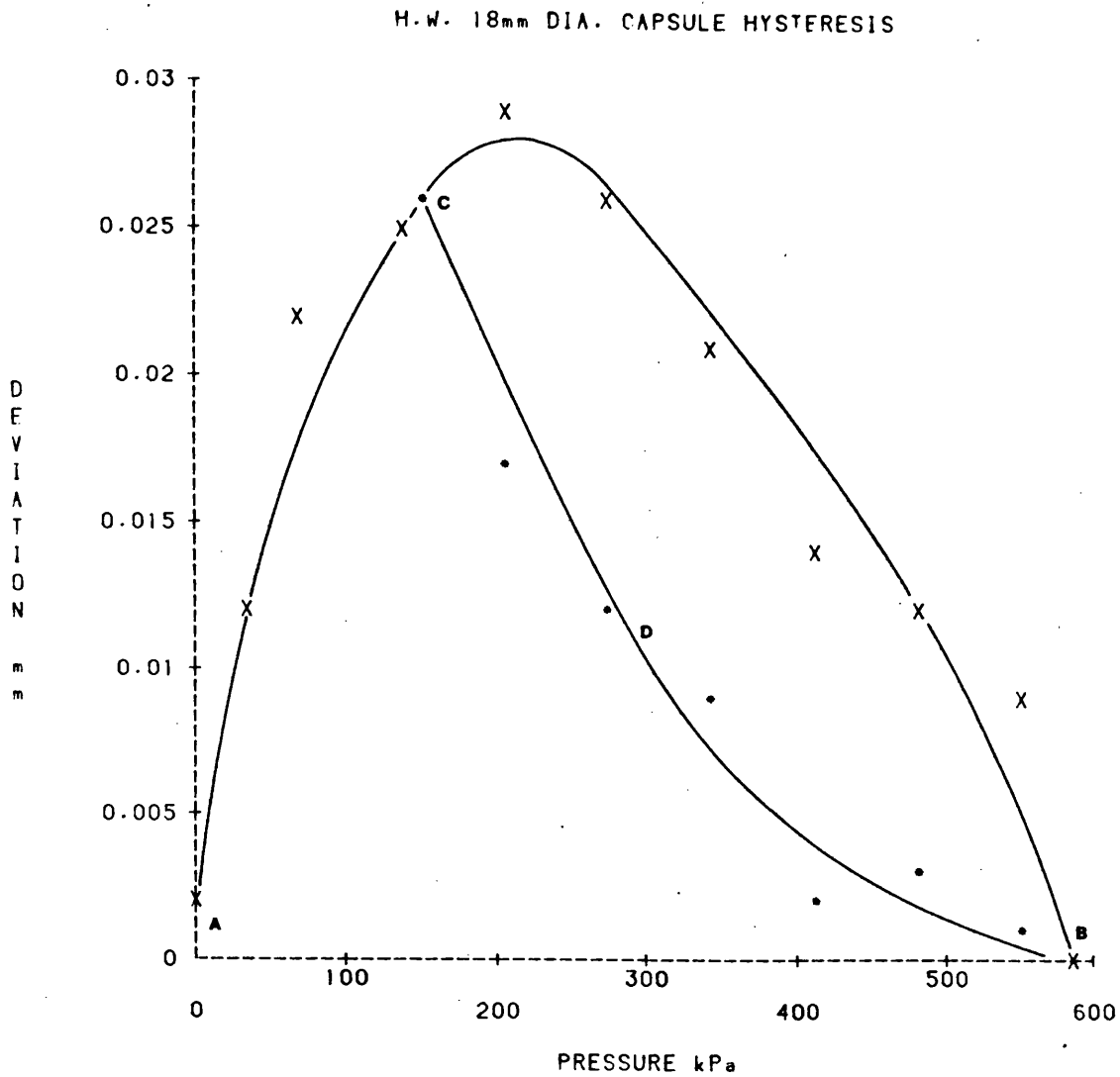
Hysteresis measurements for a standard Harper Wyman 18 mm A.I.S.I. 302 capsule.

Crosses indicate difference between extensions measured when increasing pressure from those measured when decreasing pressure.

Asterisks indicate deviation from increasing pressure extension readings, after pressurization to 586 kPa, reducing pressure to 152 kPa and then re-increasing pressure and measuring extensions.

Figure 26

WALL THICKNESS 0·4

60° INCLD.

80°

2

7

50

'NICROBRAZ LM'

CAPILLARY
0·38 BORE, 1·17 O.D.

A
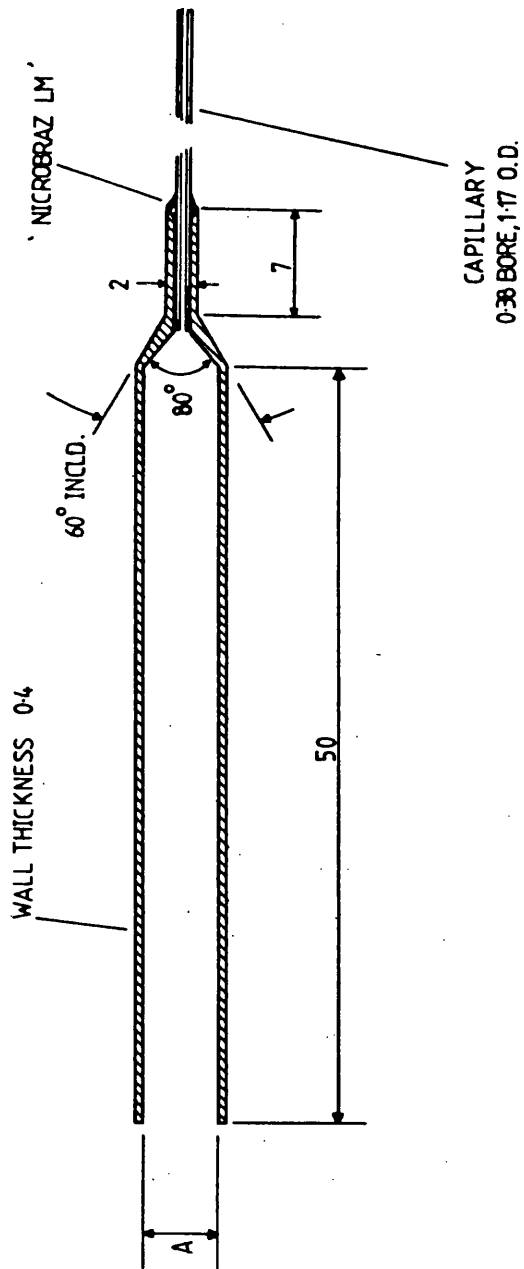
Experimental phial assembly.

A = 4 mm. Nominal volume 300 mm^3

A = 5 mm. Nominal volume 500 mm^3

Figure 27

FILLING PROCESS
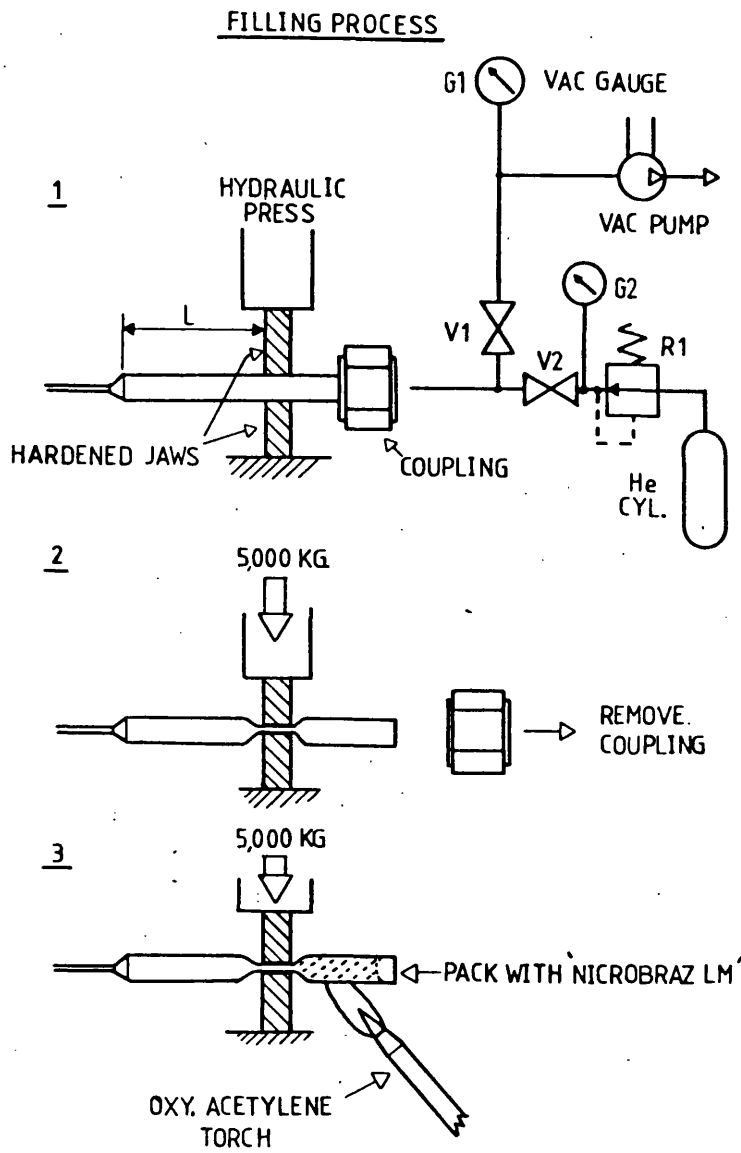
Method used to fill experimental thermal systems.

Figure 28

An experimental gas filled thermal system with a

500 mm^3 phial and a standard 18 mm diameter Harper

Wyman capsule.

Figure 29

PERFORMANCE OF THERMAL SYSTEM NO.7
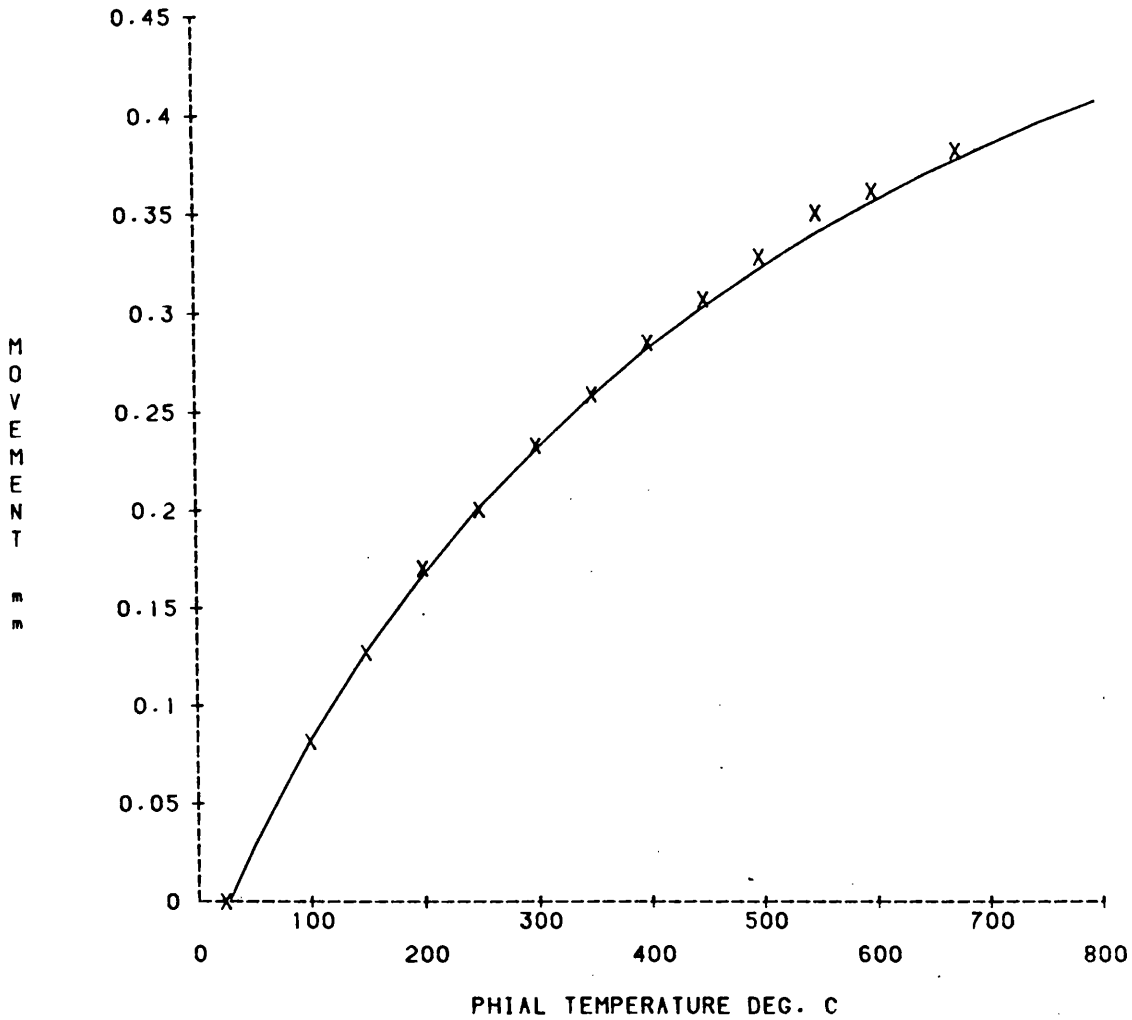
Crosses are experimental measurements.

Line is computed performance prediction based upon:-

r = 9 mm

V_p = 300 mm^3

P_f = 260 kPa abs.

U = 59 mm^3

X = 2.28 x 10^{-9} m/Pa

Figure 30

PERFORMANCE OF THERMAL SYSTEM NO.4
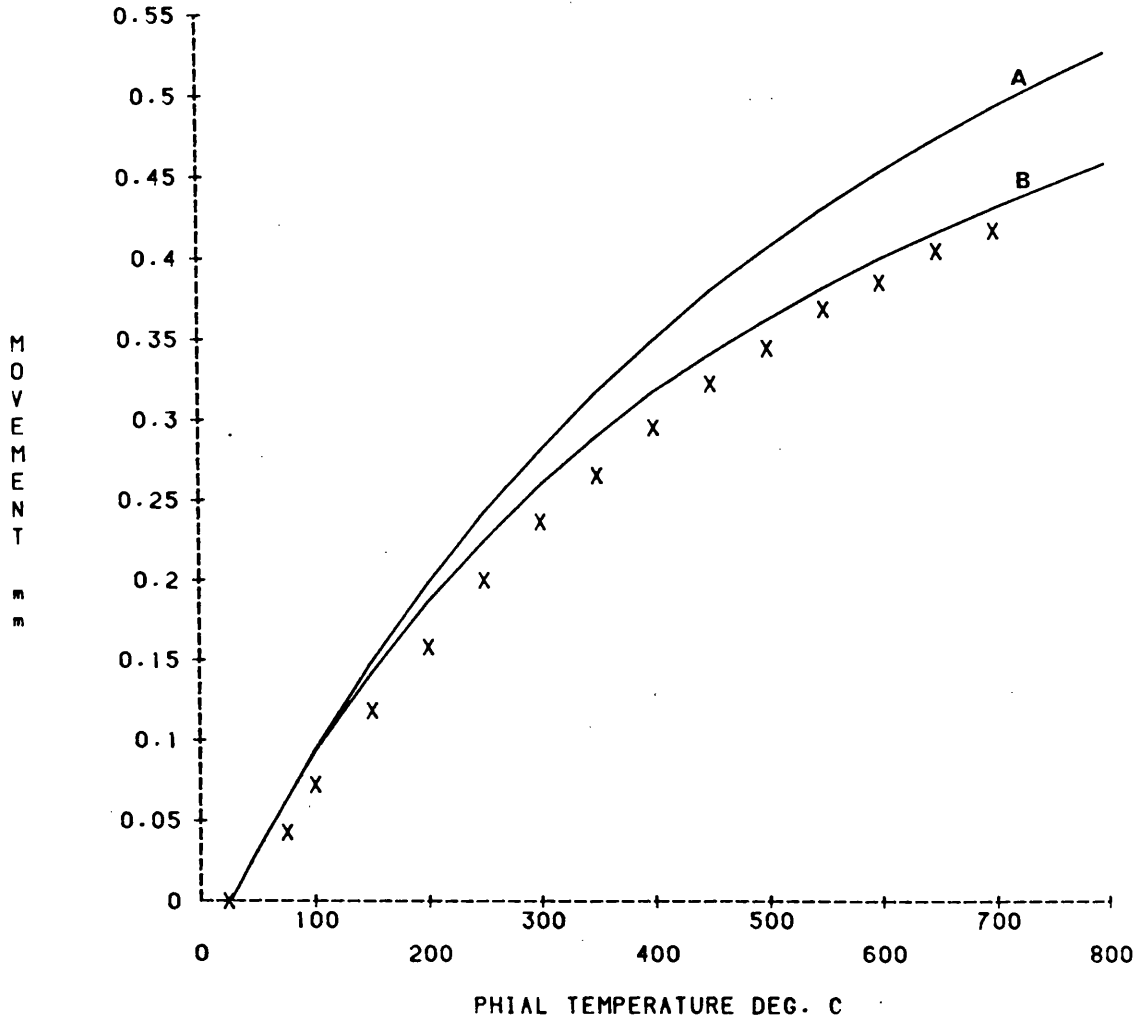
Crosses are experimental measurements.

Lines are computed performance predictions based upon:-

r = 9 mm

V_p = 500 mm^3

U = 50 mm^3

Curve A

P_f = 313 kPa abs.

X = 1.8 x 10^{-9} m/Pa

Curve B

P_f = 278 kPa abs.

Pressure-extension data
figure 21.

Figure 31

PERFORMANCE OF THERMAL SYSTEM NO.31
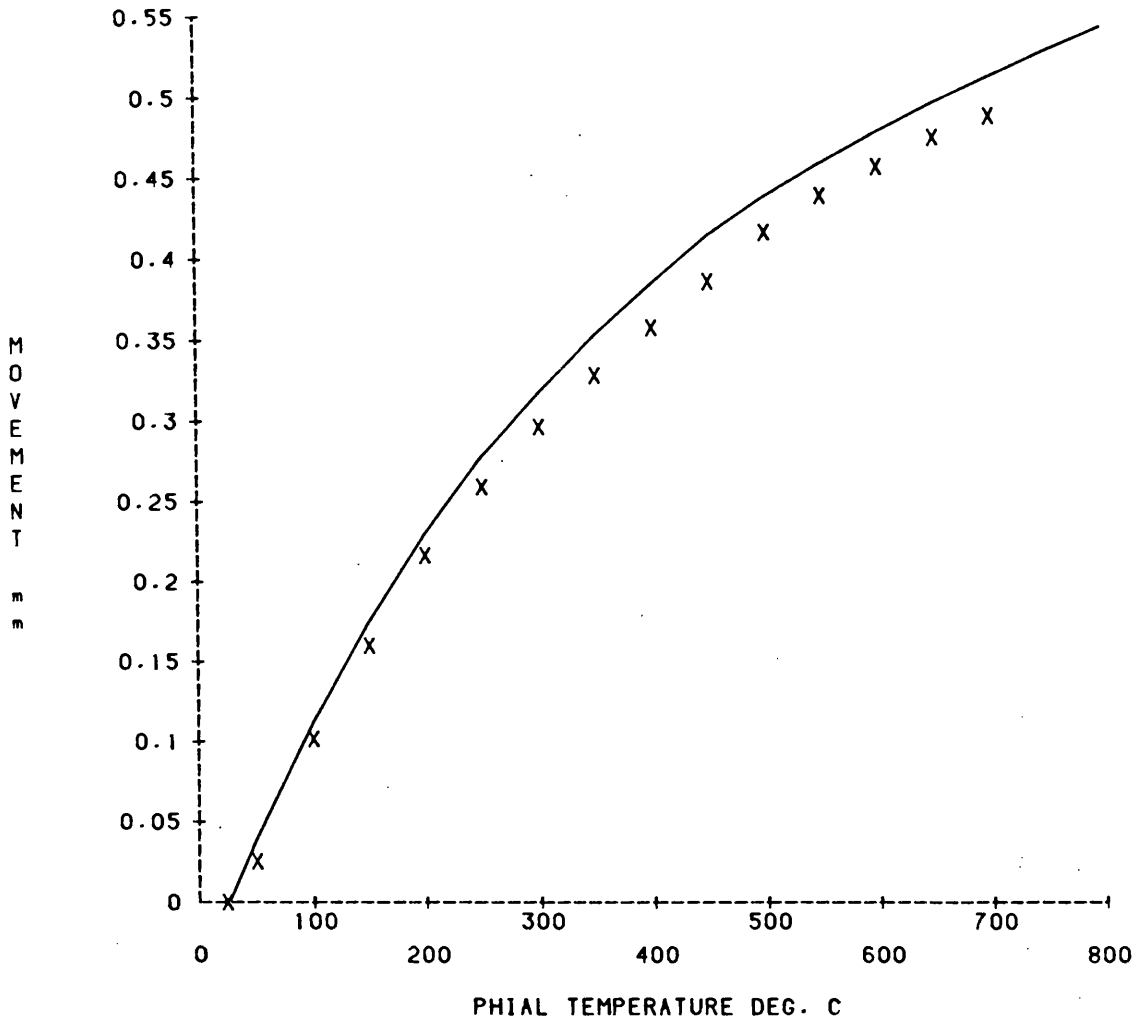
Crosses are experimental measurements.

Line is computed performance prediction based upon:-

r   = 9 mm

V_p = 500 mm^3

U   = 60 mm^3

P_f = 266 kPa abs.

Pressure-extension data figure 22.

Figure 32
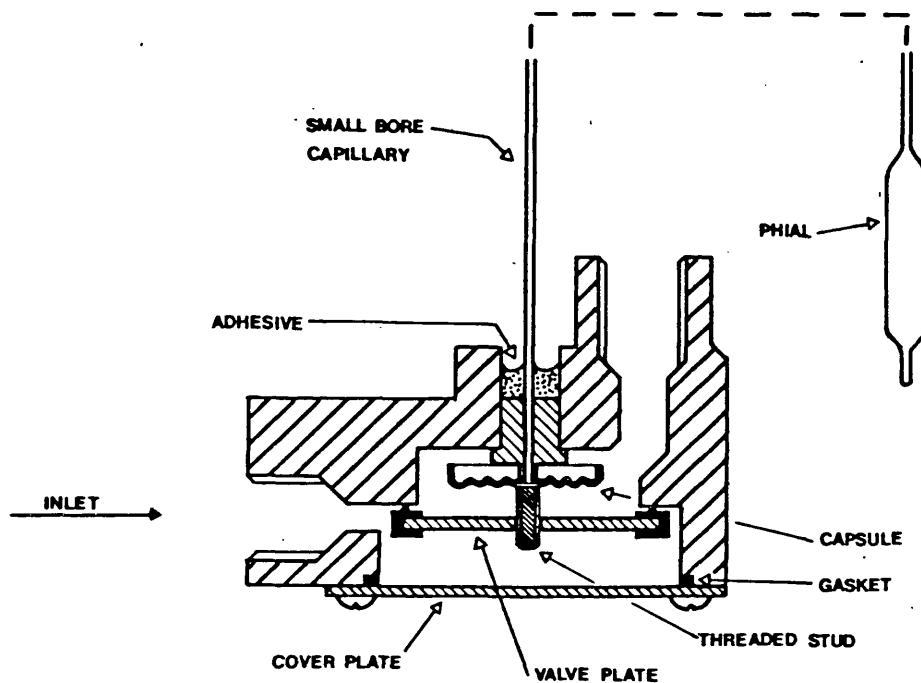
A schematic diagram of an experimental gas filled flame failure device.

Figure 33

FFD NO. 31 FLOW PERFORMANCE
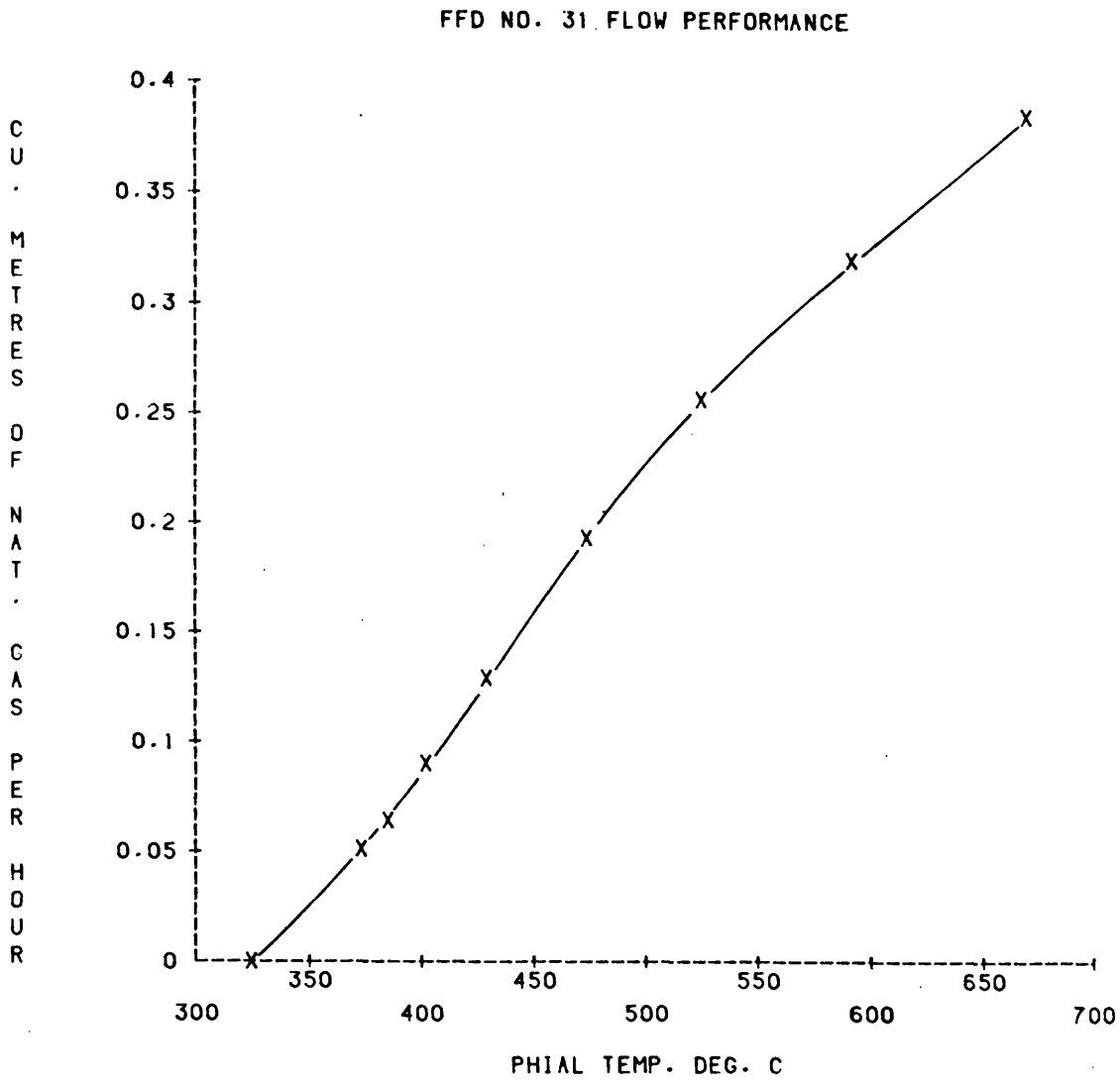
Flow performance of experimental F.F.D. number 31 at
0.75 mb pressure differential.

Figure 34

Photograph of an experimental gas filled flame failure
device with a 500 mm^3 phial.
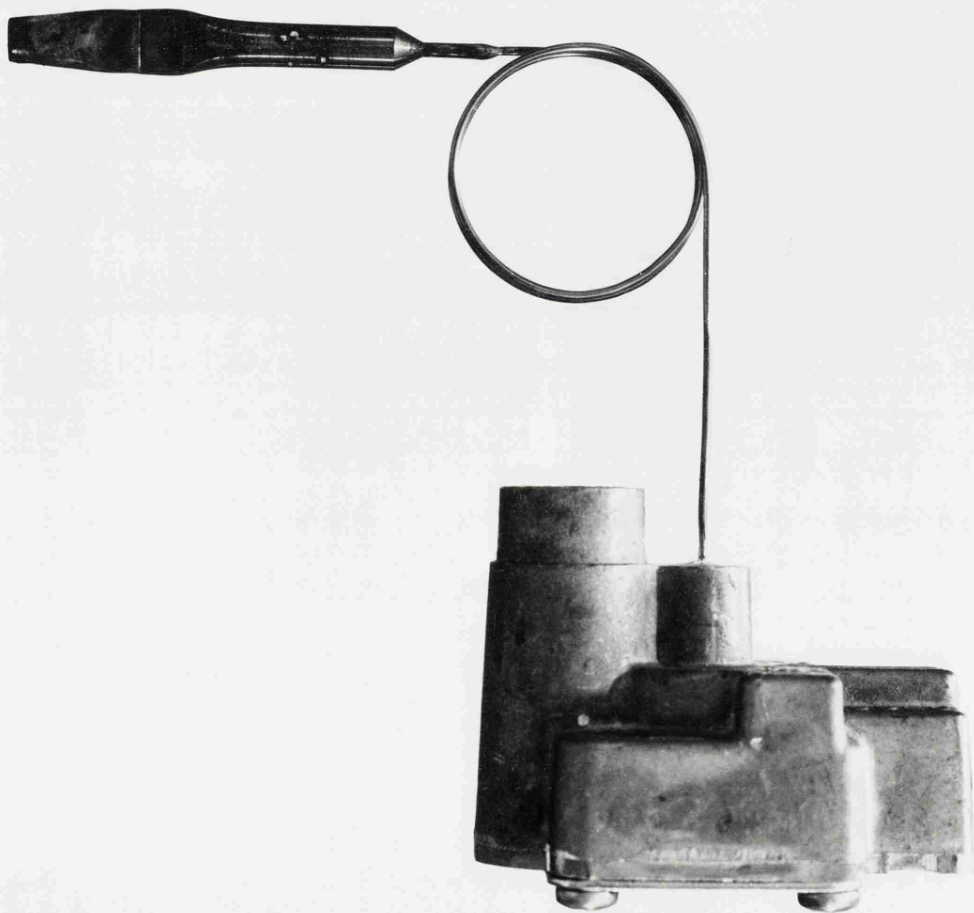
Figure 35

PHIAL COOLING RATES
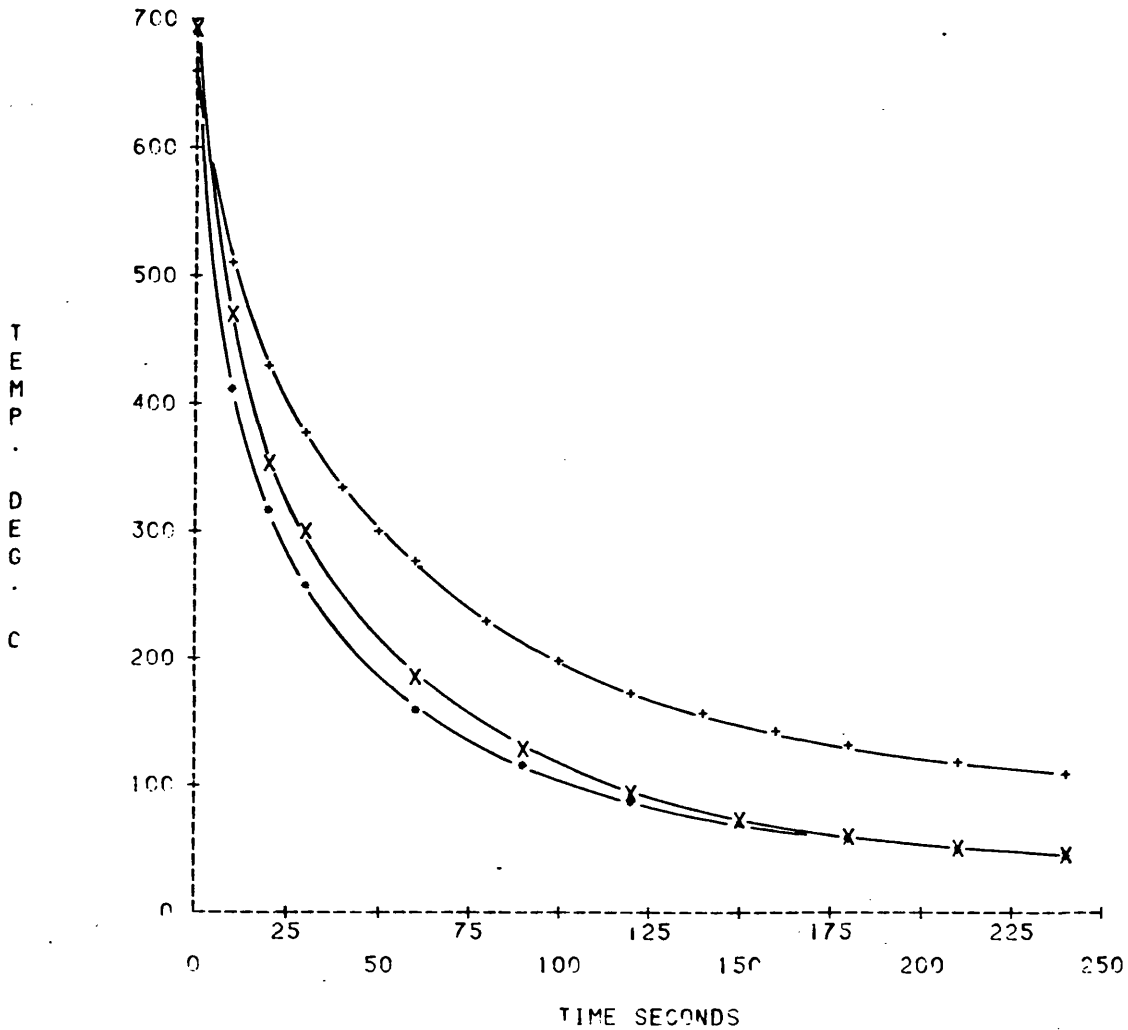
The cooling rates of experimental F.F.D. phials.

+ 300 mm^3 phial in gas oven at 250 ^{o}C C.O.T.

X 300 mm^3 phial in air at 22 ^{o}C

* 500 mm^3 phial in air at 22 ^{o}C

Figure 36

VARIATION OF CAPSULE VOL. WITH EXTENSION
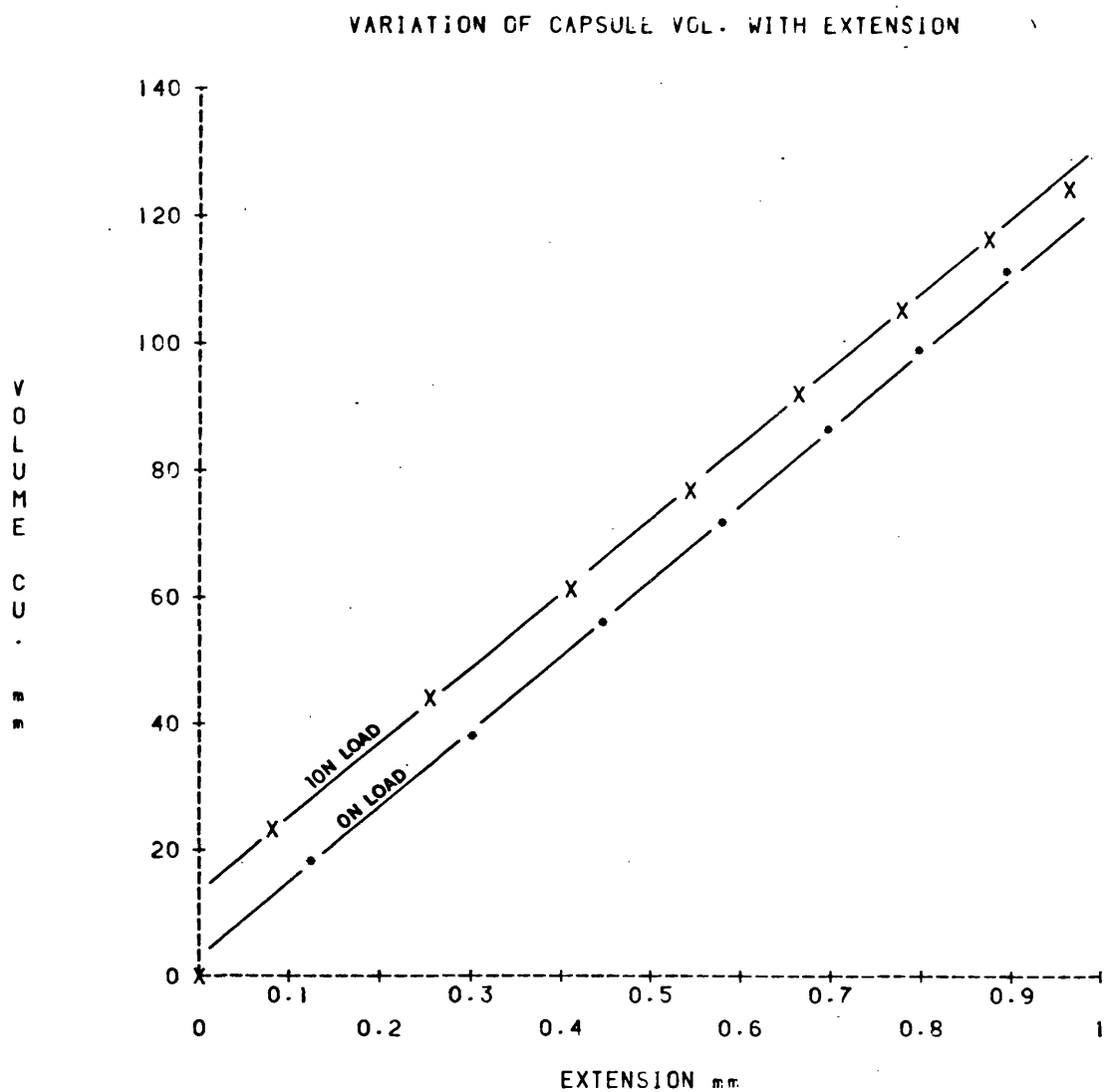
The volume-extension relationship for Harper Wyman 18 mm diameter capsules.

Figure 37
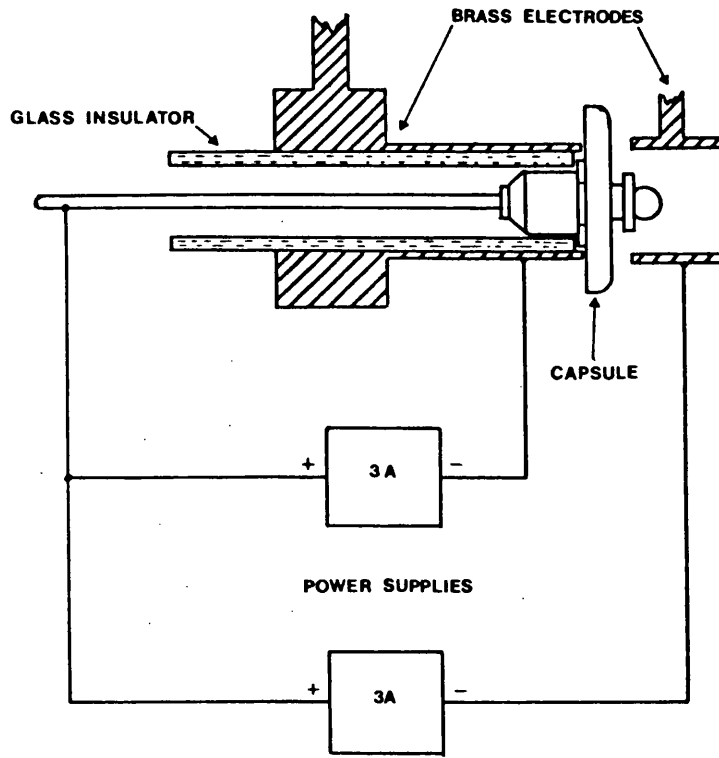
The apparatus used for electropolishing Harper Wyman
18 mm diameter capsules.

Figure 38
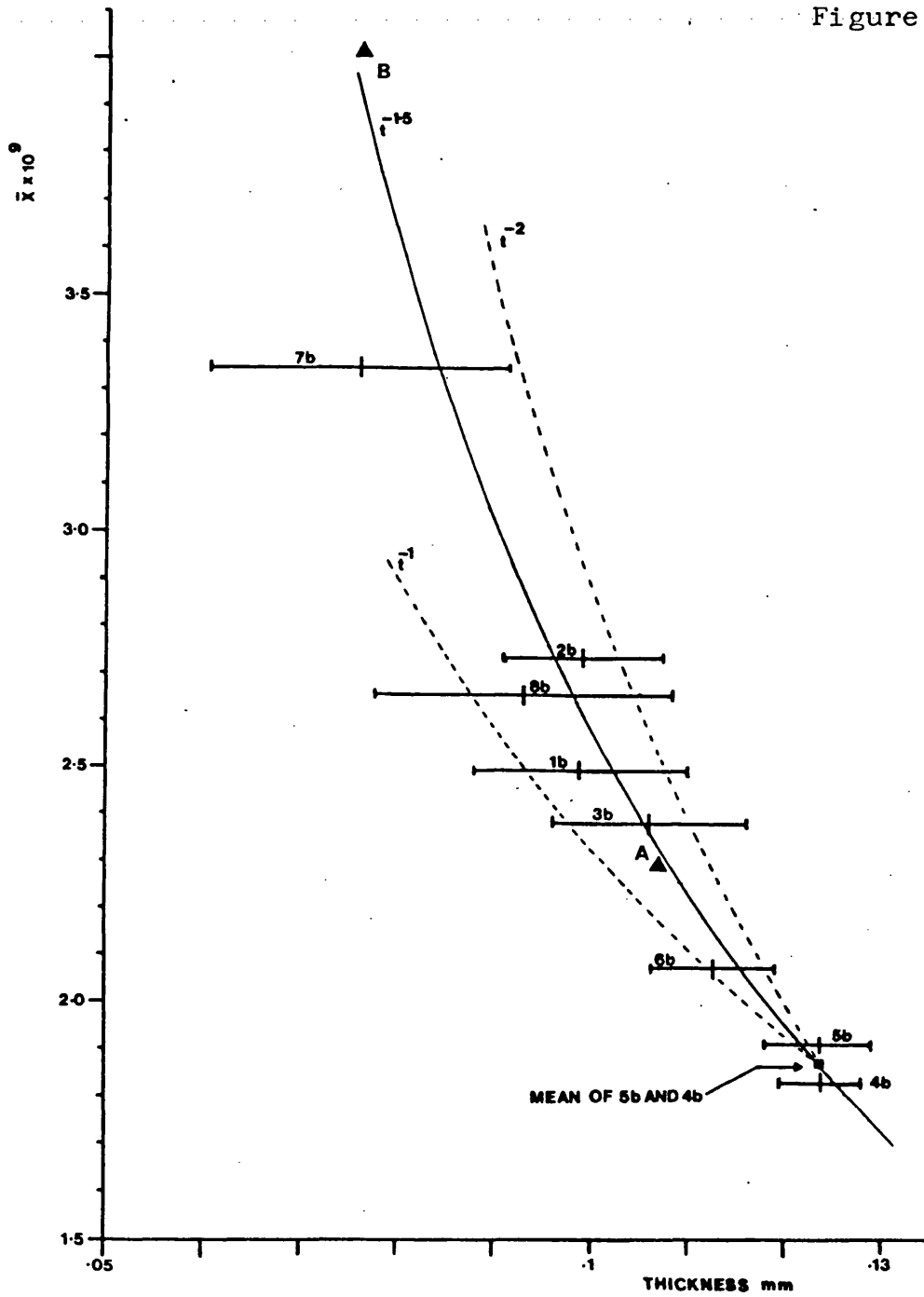
The relationship between the diaphragm thickness and
the mean pressure sensitivity of Harper Wyman 18 mm
diameter capsules.

Figure 39

CONST. DEFLECTION PRESSURE/LOAD CHARACTERISTICS
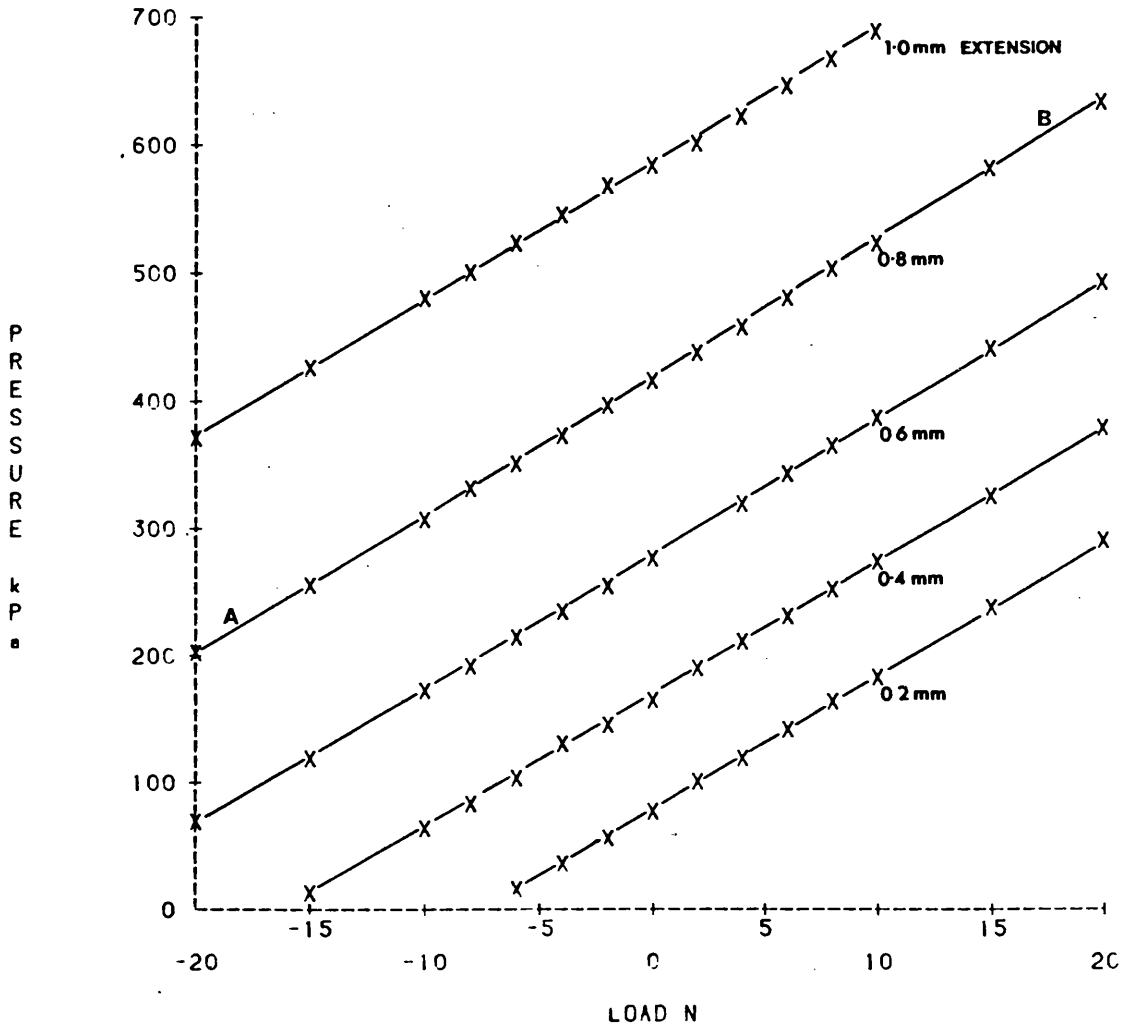
The relationship between pressure and load at constant capsule extension for Harper Wyman 18 mm diameter capsules.
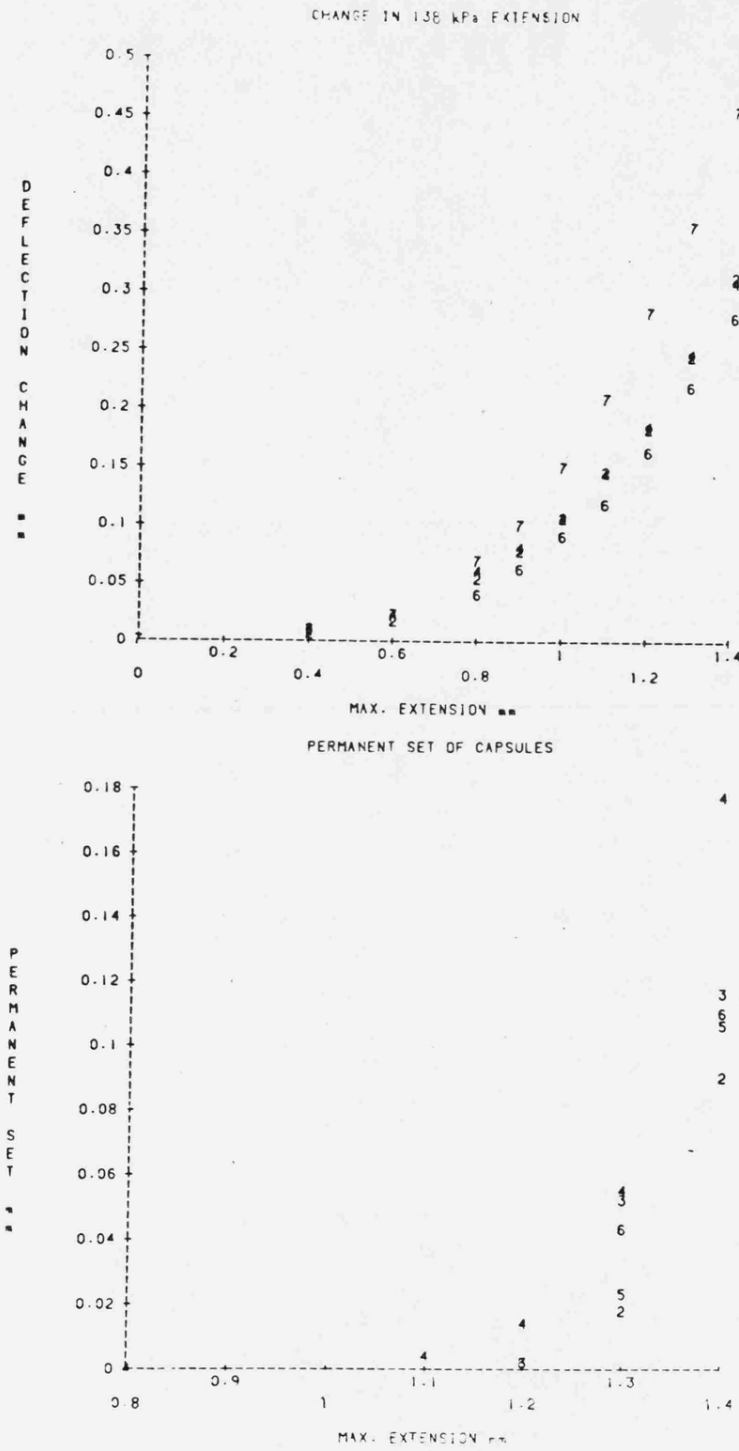
The change in 138 kPa deflection and permanent set of some 18 mm diameter Harper Wyman capsules.
The numerals indicate the sample number

Figure 40
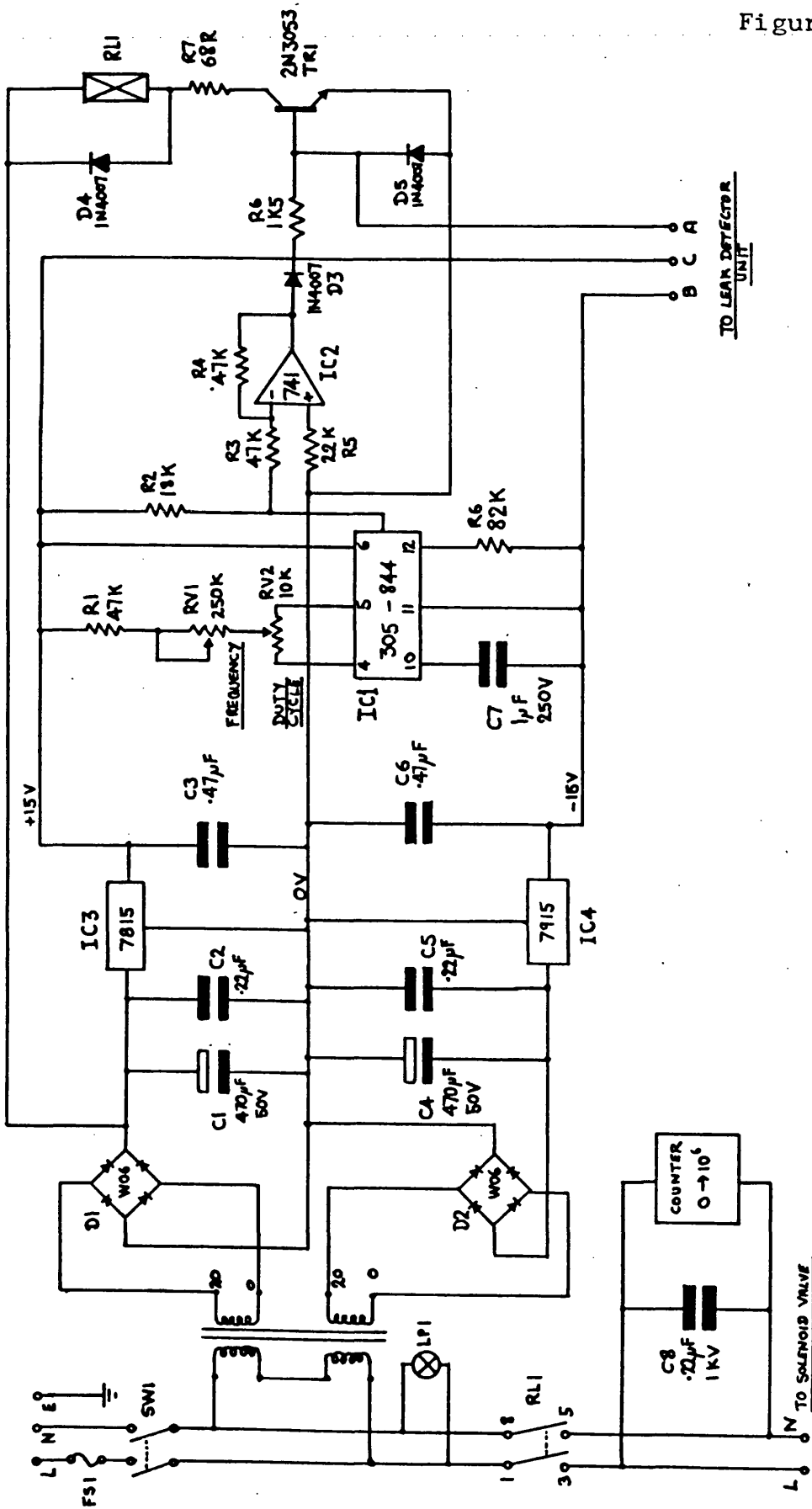
Figure 41

Cycling control unit for capsule fatigue testing rig.

Figure 42
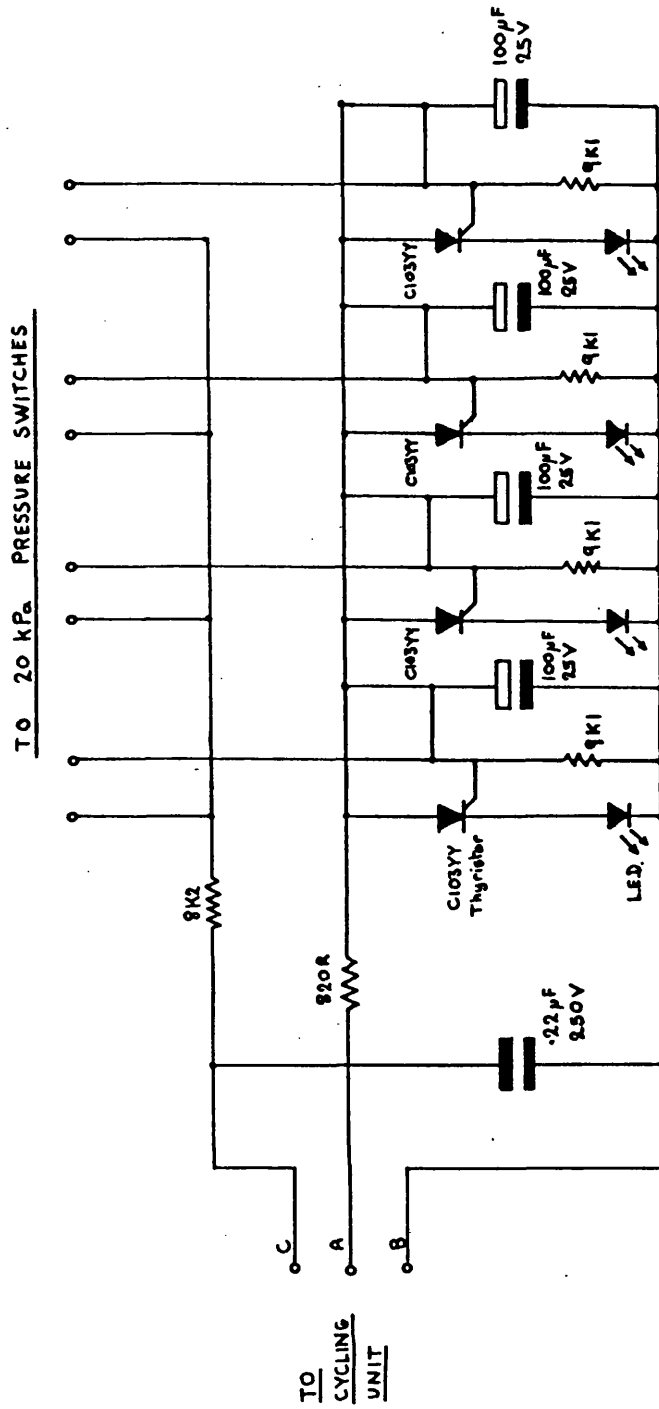
Capsule leak detector unit.

Figure 43
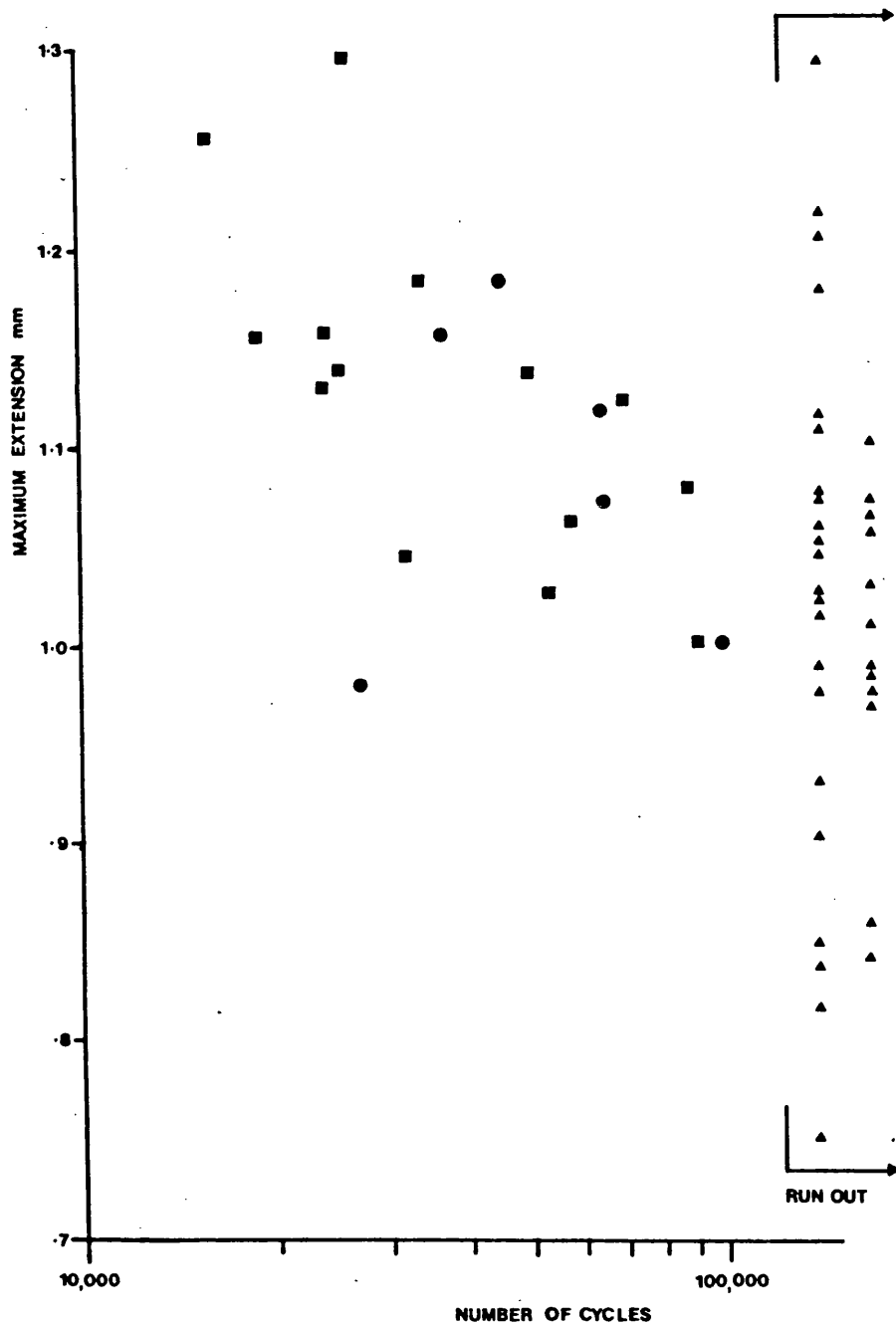
The distribution of failures which occurred during testing
of Harper Wyman 18 mm diameter capsules.

■ Top boss weld failure

● Other failure

Figure 44
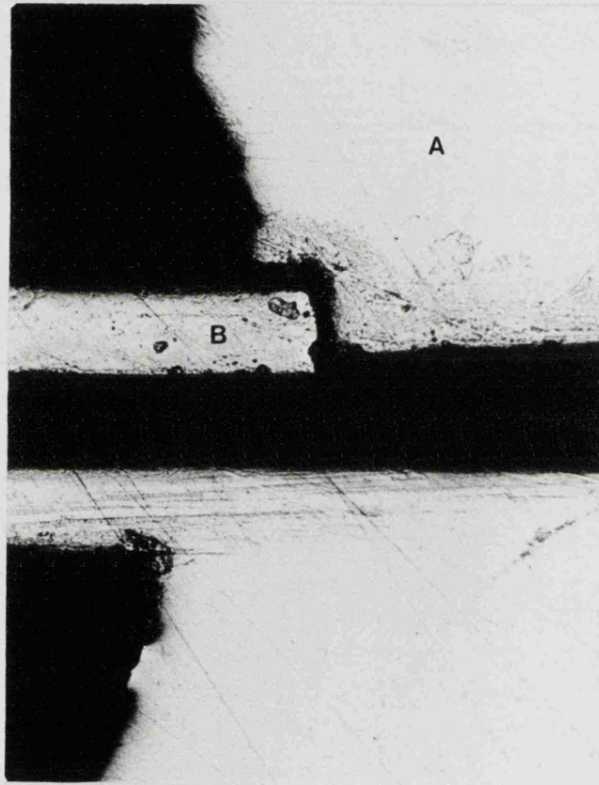
Crack in weld joining top boss (A) to upper diaphragm (B).

Figure 45
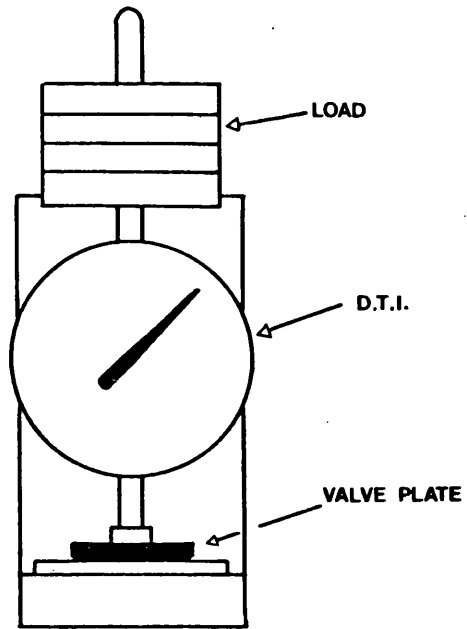
The apparatus for the measurement of the compliance of rubber valve seals.

Figure 46

VALVE SEAL COMPLIANCE
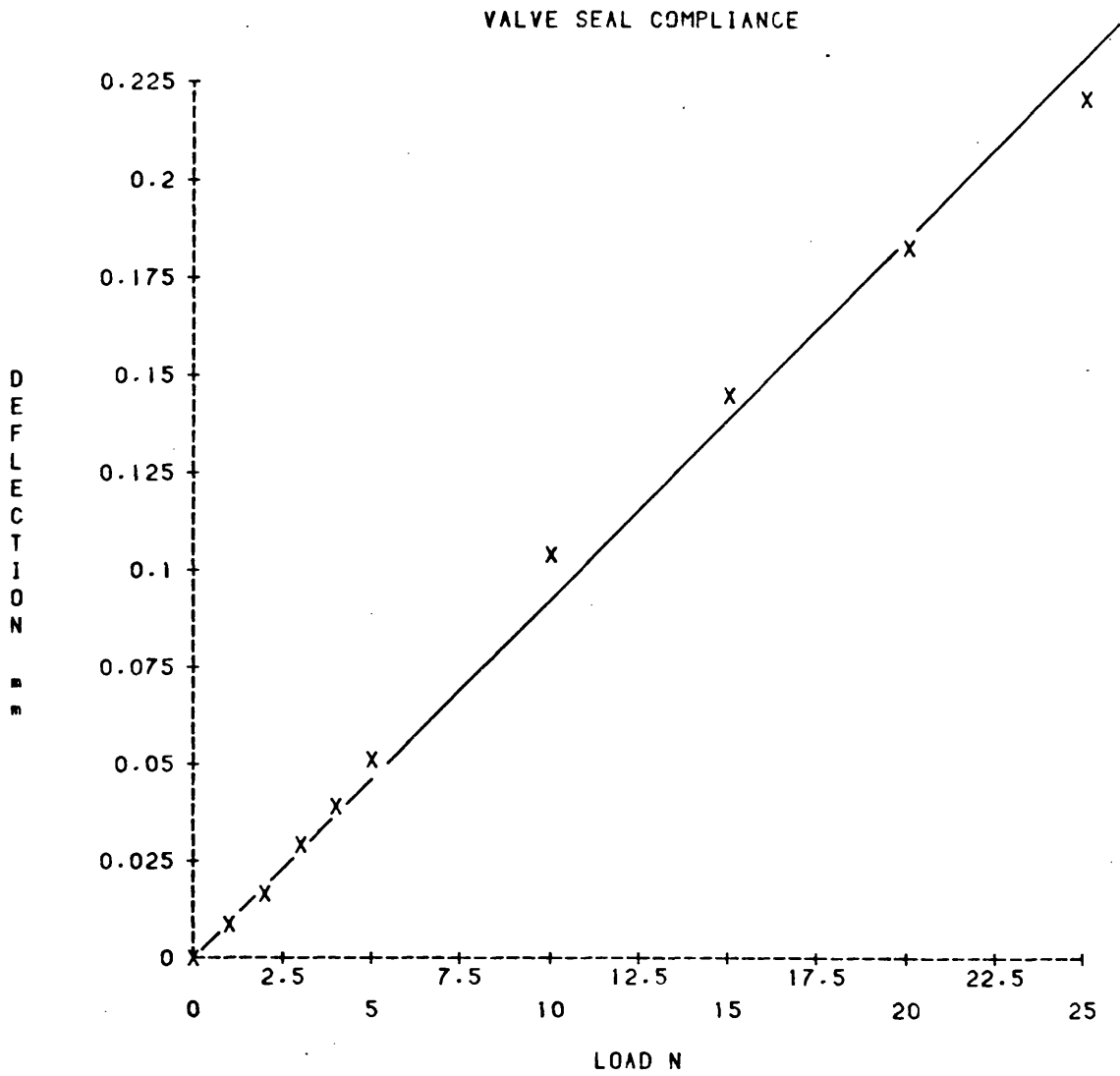
The deflection versus load for a standard Harper Wyman
valve plate (see fig. 18).

Figure 47
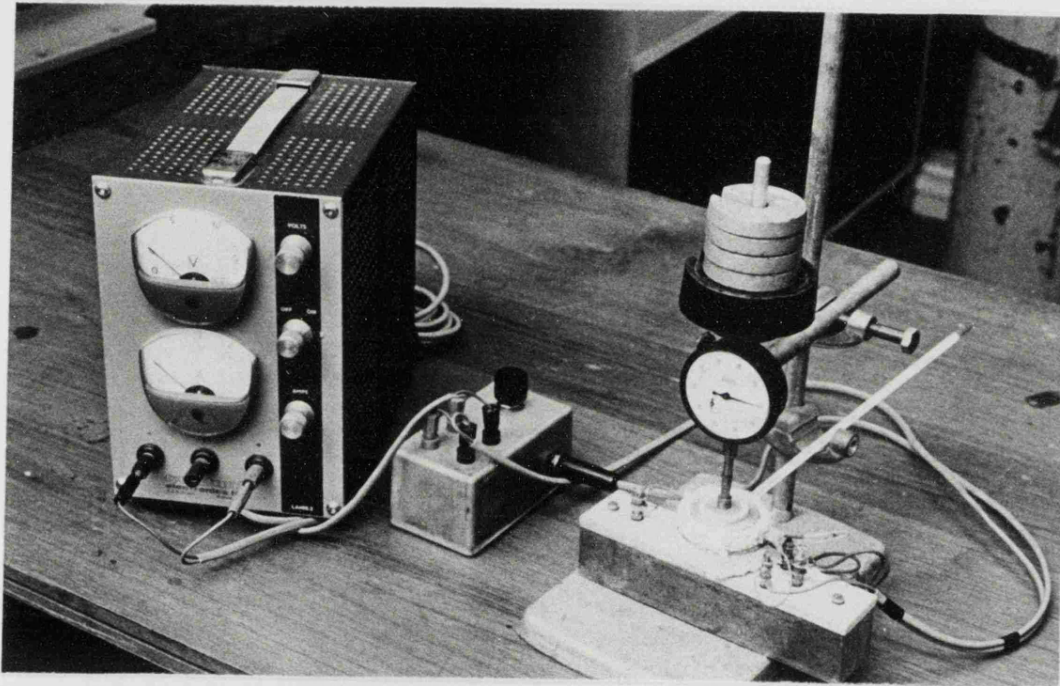
Apparatus for measuring the creep rate of rubber valve seals.

Figure 48
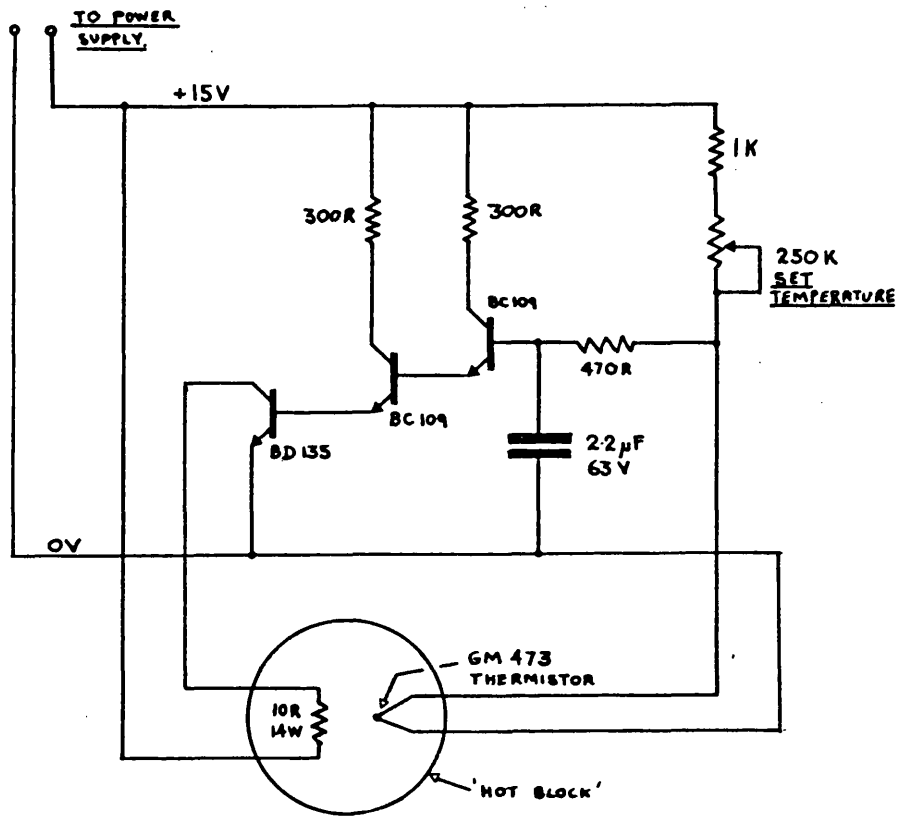
Temperature control circuit for the creep measurement apparatus.

Figure 49
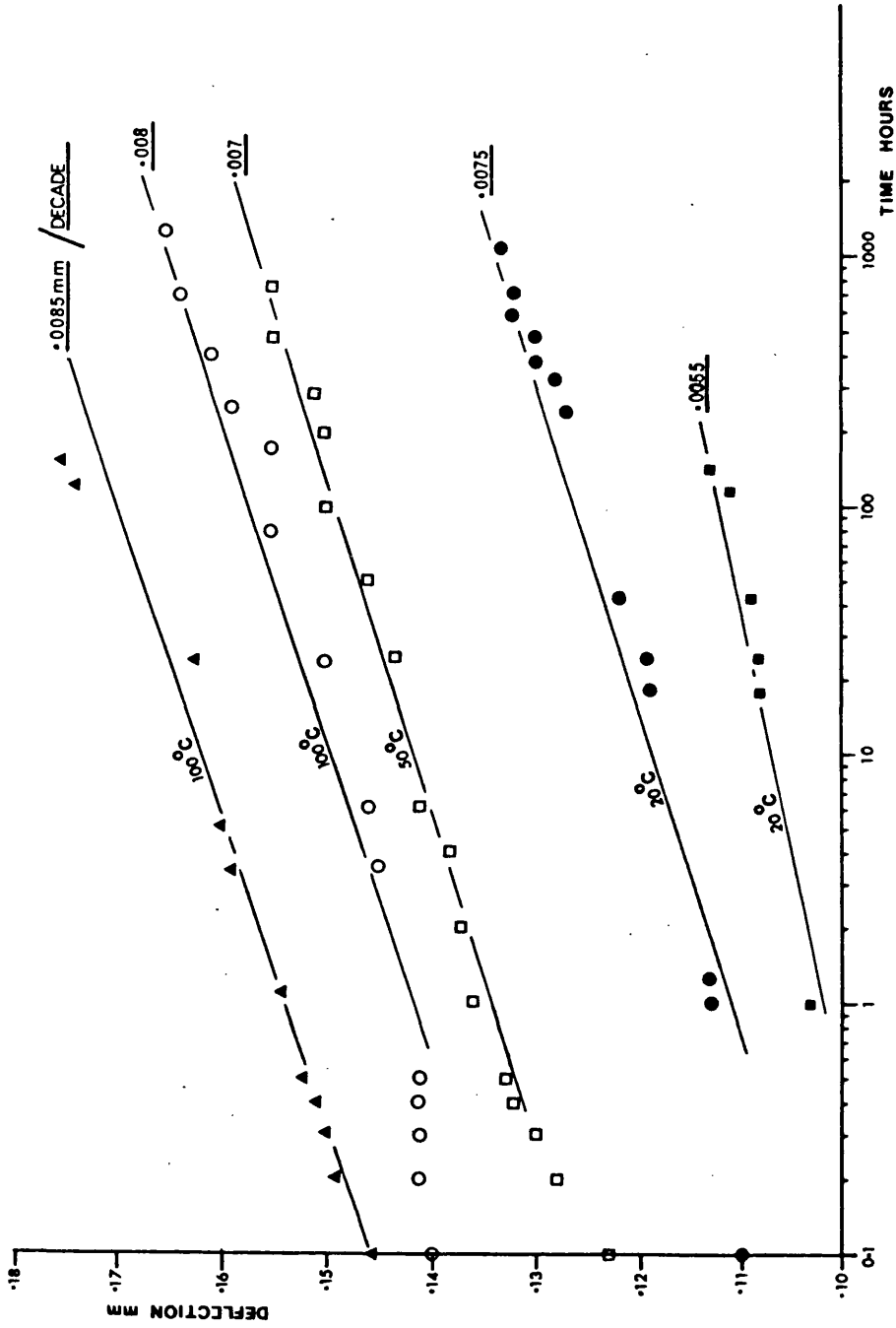
The creep rates of silicone rubber valve seals when subjected to
a 10N load at various temperatures.

Figure 50

VALVE SEAL THERMAL EXPANSION
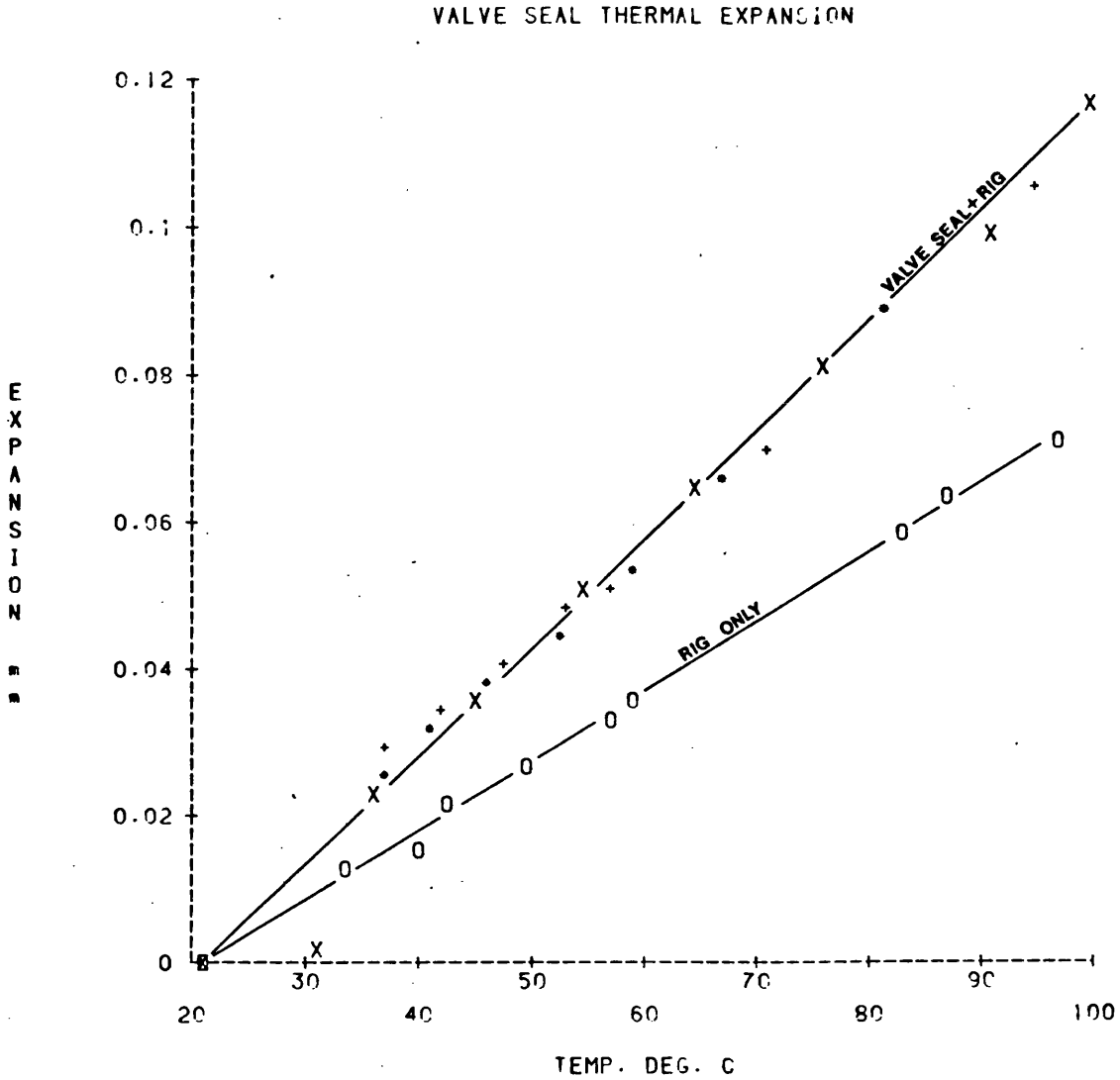
Measurements of the thermal expansion of silicone rubber valve seals.

Sample number 1 = X
Sample number 2 = *
Sample number 3 = +

Figure 51
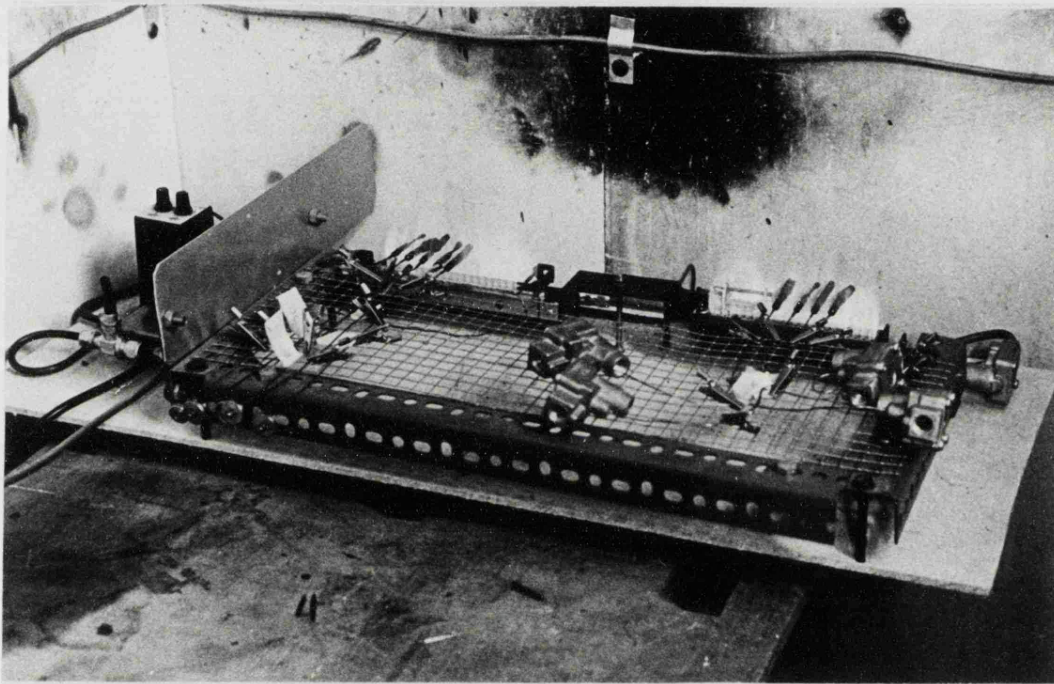
The long term burner test rig.
Thermal systems undergoing continuous flame testing can
be seen on the left hand side of the equipment.
Completed valves undergoing cycling flame testing can
be seen on the right hand side.

Figure 52
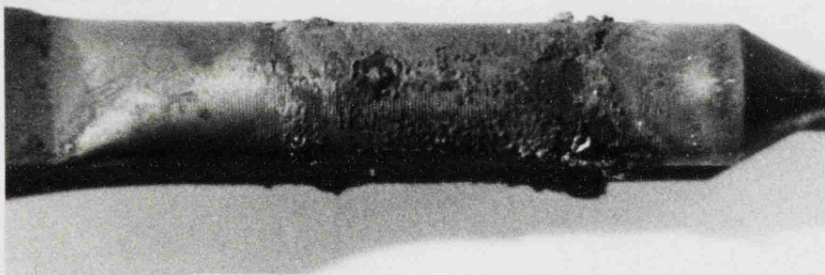
Condition of 500 mm^3 phial after running continuously
at 700 ^{o}C in a gas flame for 2,700 hours.

Figure 53

VARIATION OF STROKE WITH CAPSULE DIAMETER
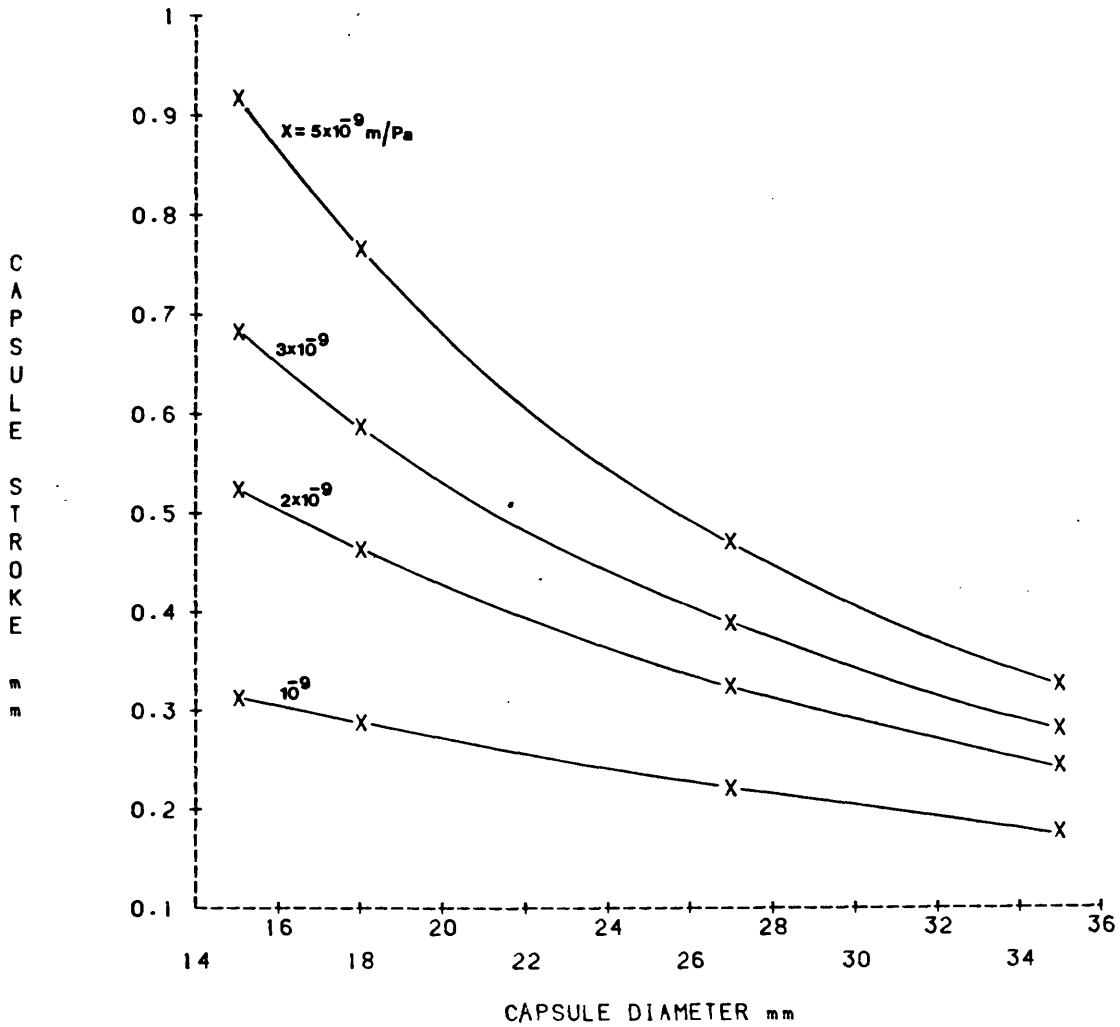
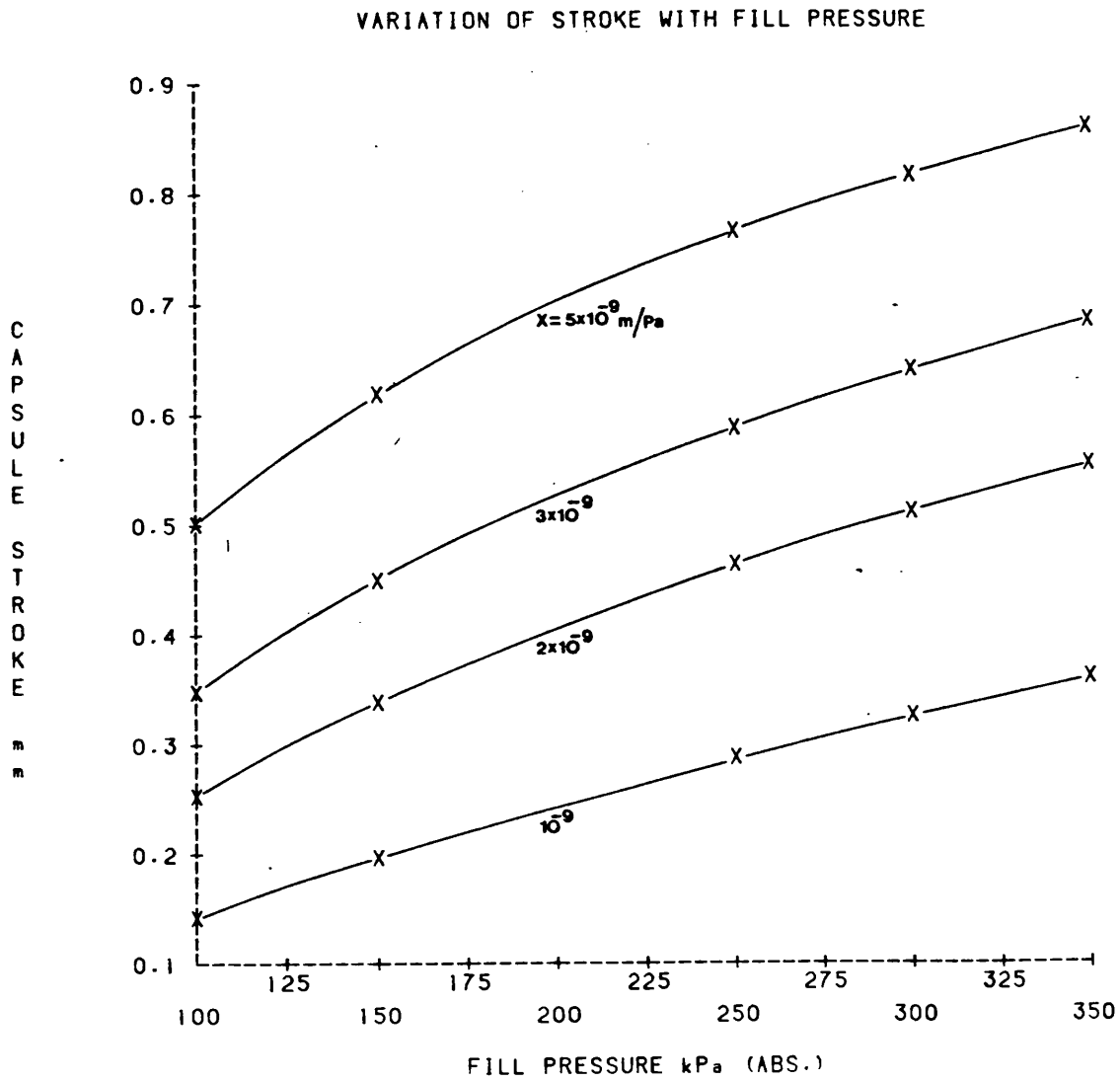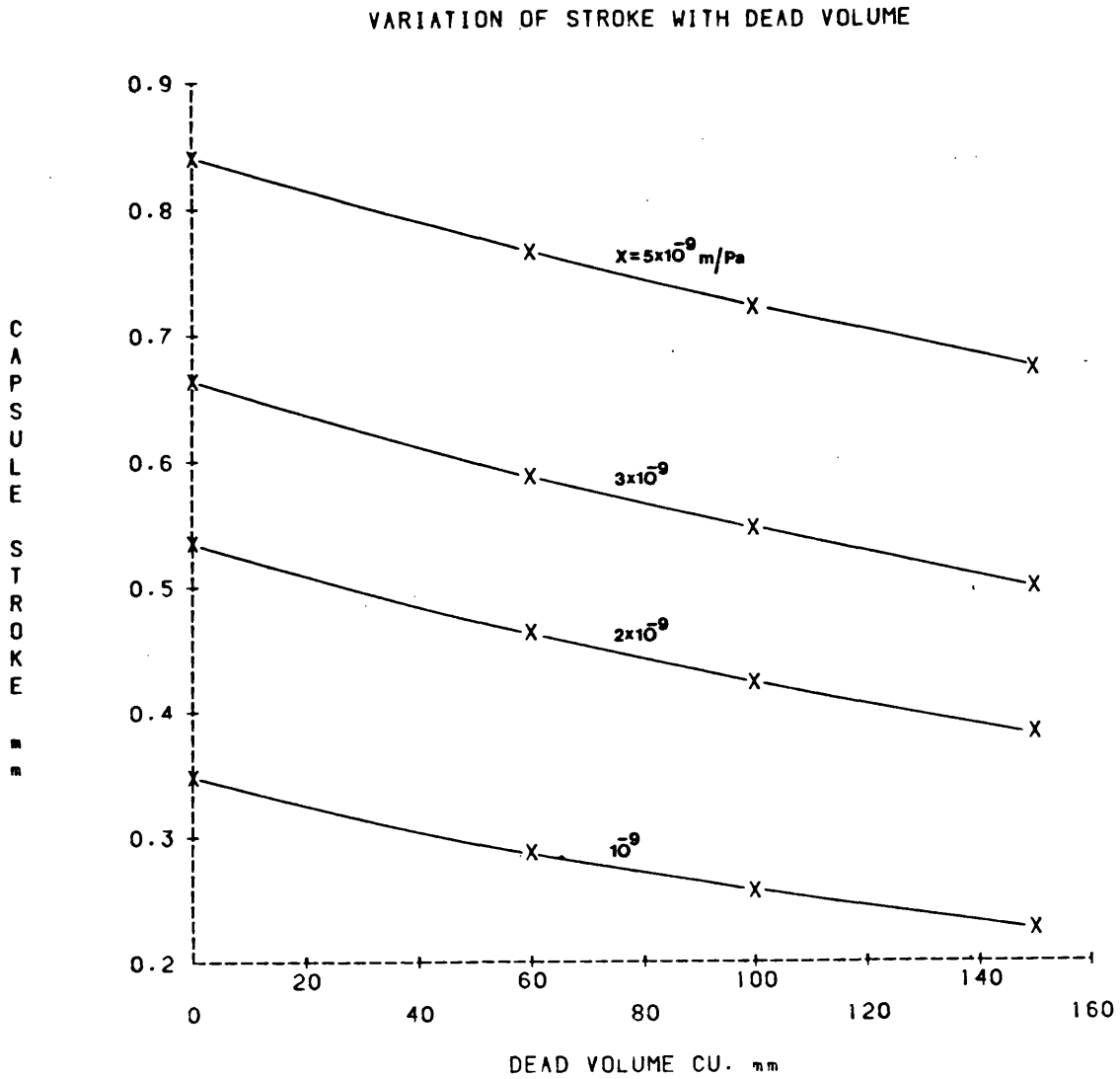The variation of capsule 27 to 700 $^\circ$C stroke with capsule diameter.

The other thermal system parameters were:-

$$V_p = 500 \text{ mm}^3$$
$$P_f = 250 \text{ kPa abs.}$$
$$U = 60 \text{ mm}^3$$

Figure 54

VARIATION OF STROKE WITH PHIAL VOLUME
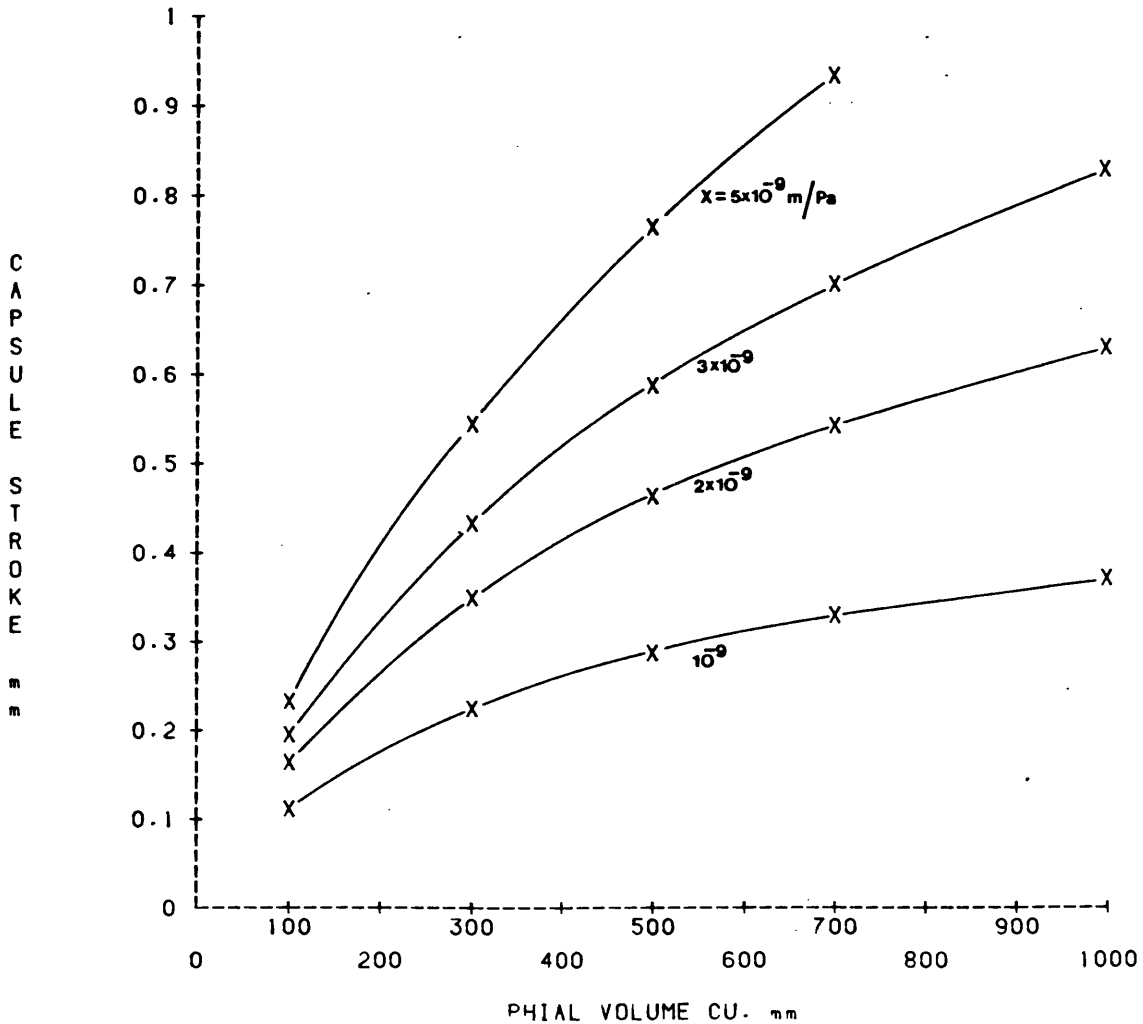
The variation of capsule 27 to 700 $^{\circ}$C stroke with phial volume.

The other thermal system parameters were:-

$r = 9$ mm

$P_f = 250$ kPa abs.

$U = 60$ mm^3

Figure 55

VARIATION OF STROKE WITH FILL PRESSURE

The variation of capsule 27 to 700 $^{\circ}$C stroke with fill pressure.
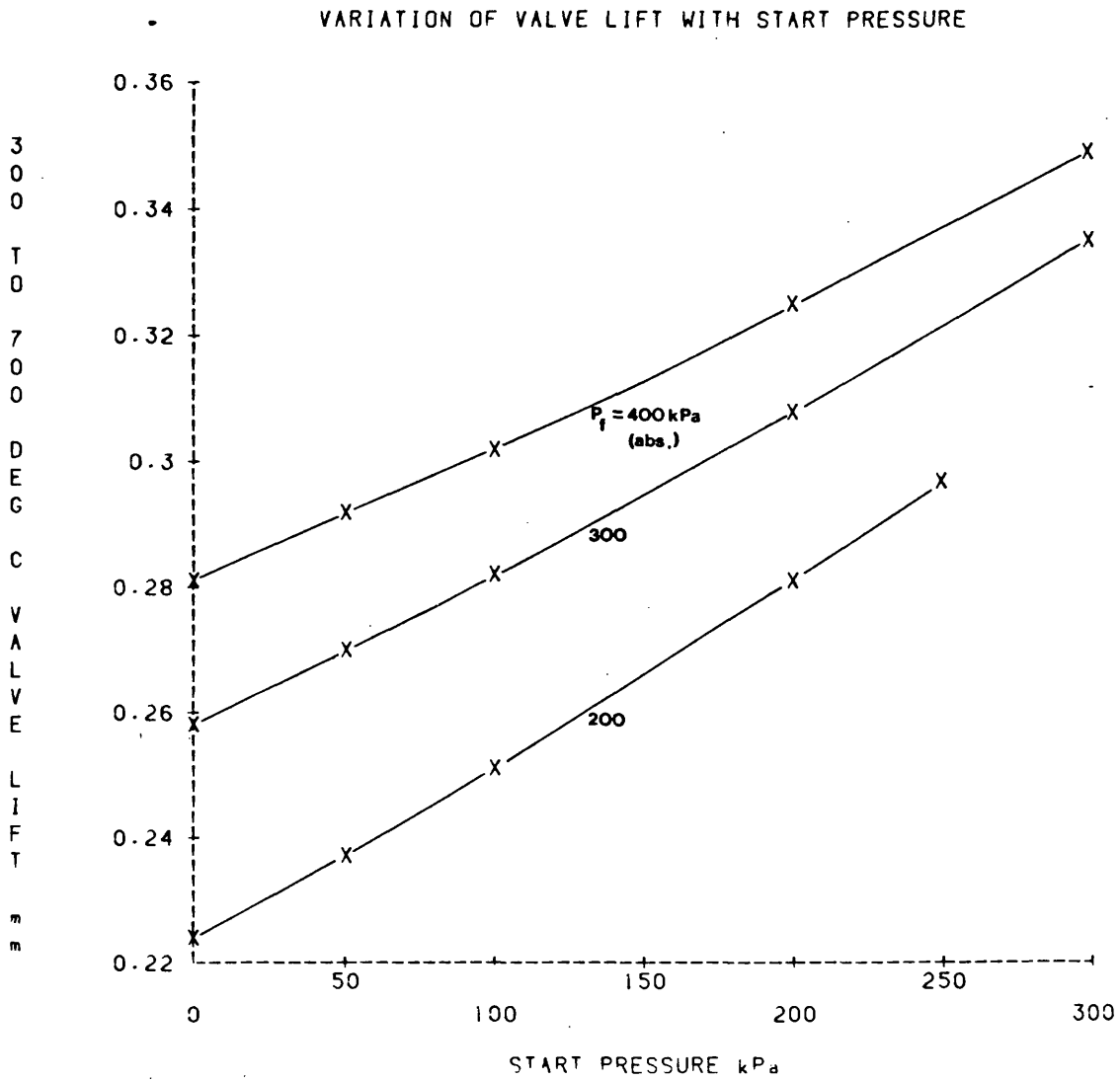
The other thermal system parameters were:-

$$r = 9 \text{ mm}$$
$$V_p = 500 \text{ mm}^3$$
$$U = 60 \text{ mm}^3$$

Figure 56

VARIATION OF STROKE WITH DEAD VOLUME

The variation of capsule 27 to 700 °C stroke with dead
volume.
The other thermal system parameters were :-

$$r = 9mm$$
$$V_p = 500 \ mm^3$$
$$P_f = 250 \ kPa \ abs.$$

Figure 57

VARIATION OF VALVE LIFT WITH START PRESSURE

The variation of 300 to 700 ^{O}C valve lift with starting pressure (P_s).
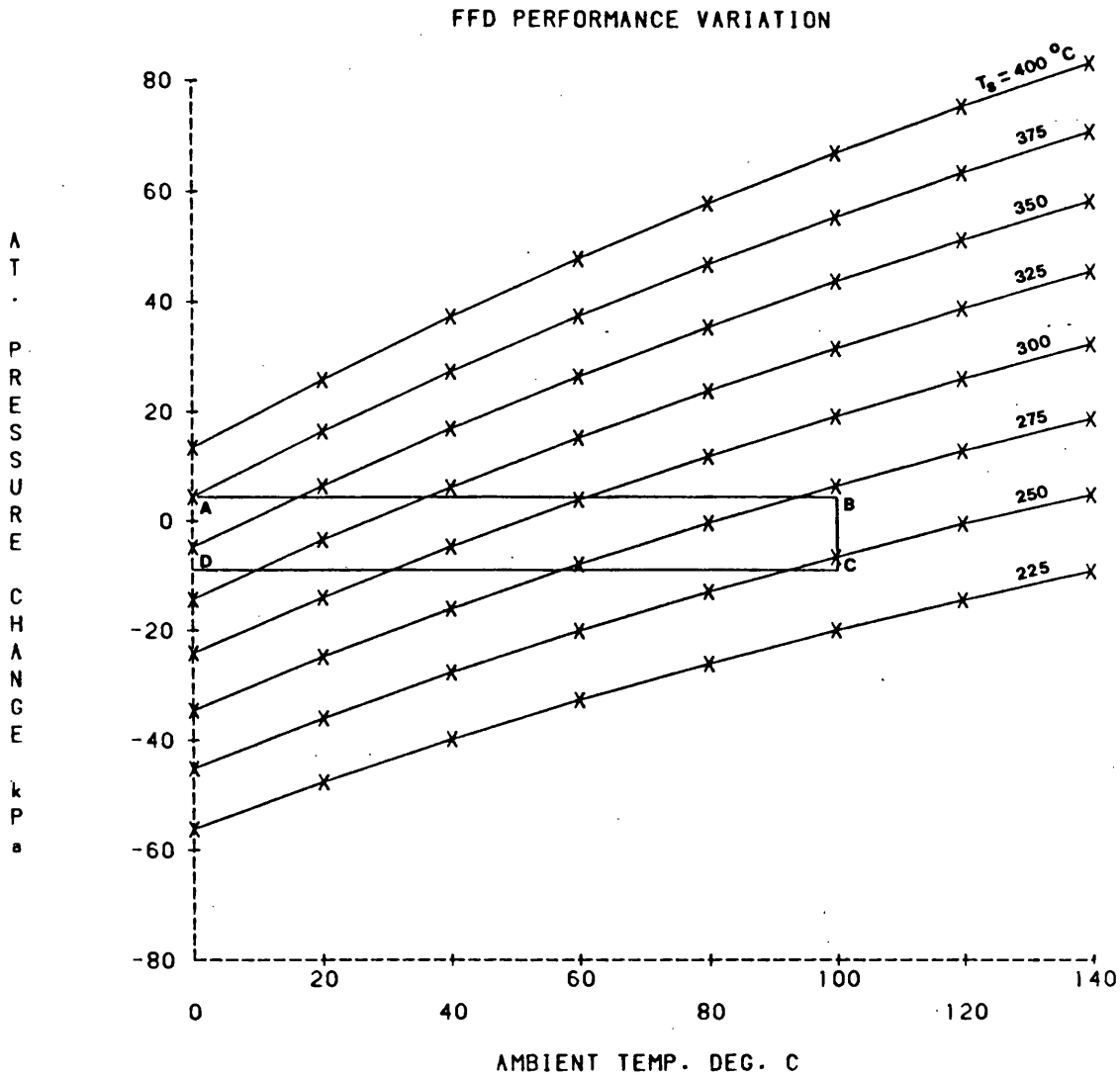
The other thermal system parameters were:-

$$r = 9 \text{ mm}$$
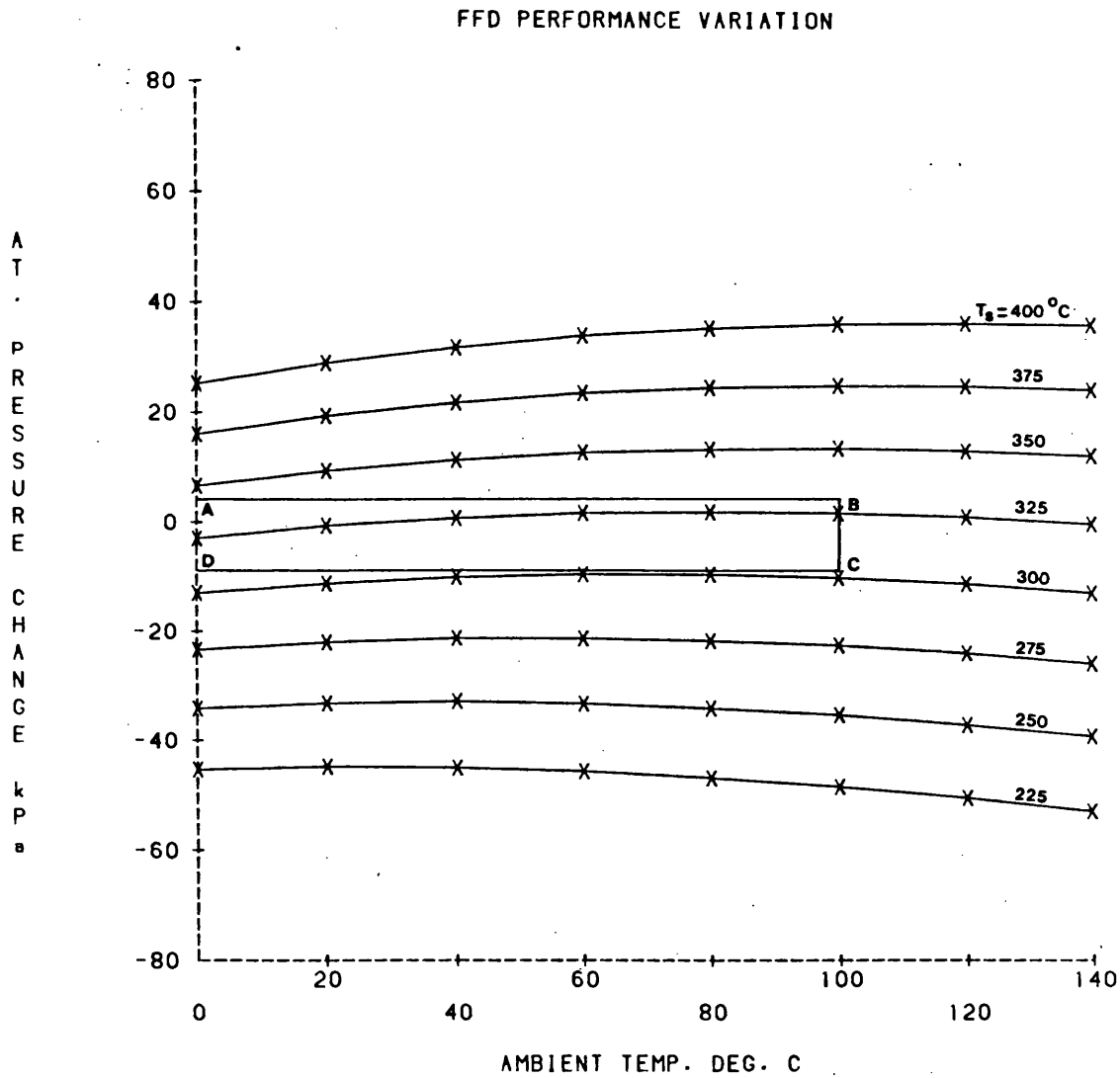$$V_p = 500 \text{ mm}^3$$
$$U = 60 \text{ mm}^3$$
$$X = 3 \times 10^{-9} \text{ m/Pa}$$

Figure 58

FFD PERFORMANCE VARIATION

The variation of opening temperature with atmospheric
pressure and ambient temperature for F.F.D. number 31
without any temperature compensation.
The rectangle ABCD indicates the range of operating
conditions likely to be encountered in the U.K.
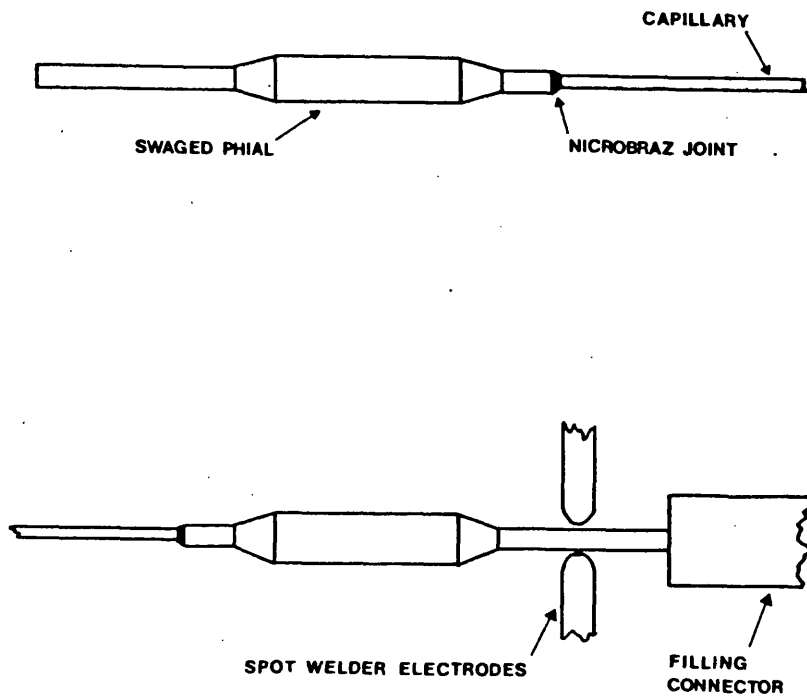
Figure 59

FFD PERFORMANCE VARIATION

The variation of opening temperature for F.F.D. number
31 with a temperature compensation factor of 0.0007
mm/degree C.
The approximate reduction of atmospheric pressure with
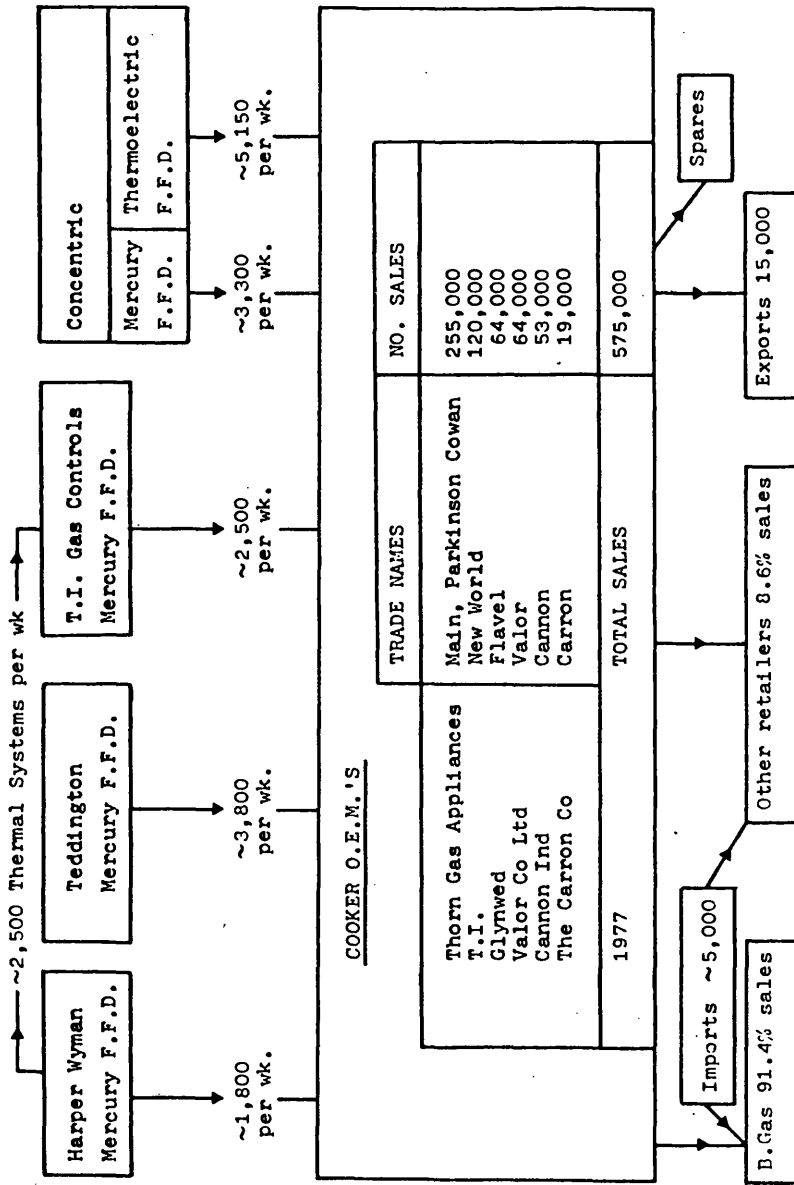altitude is as follows:-
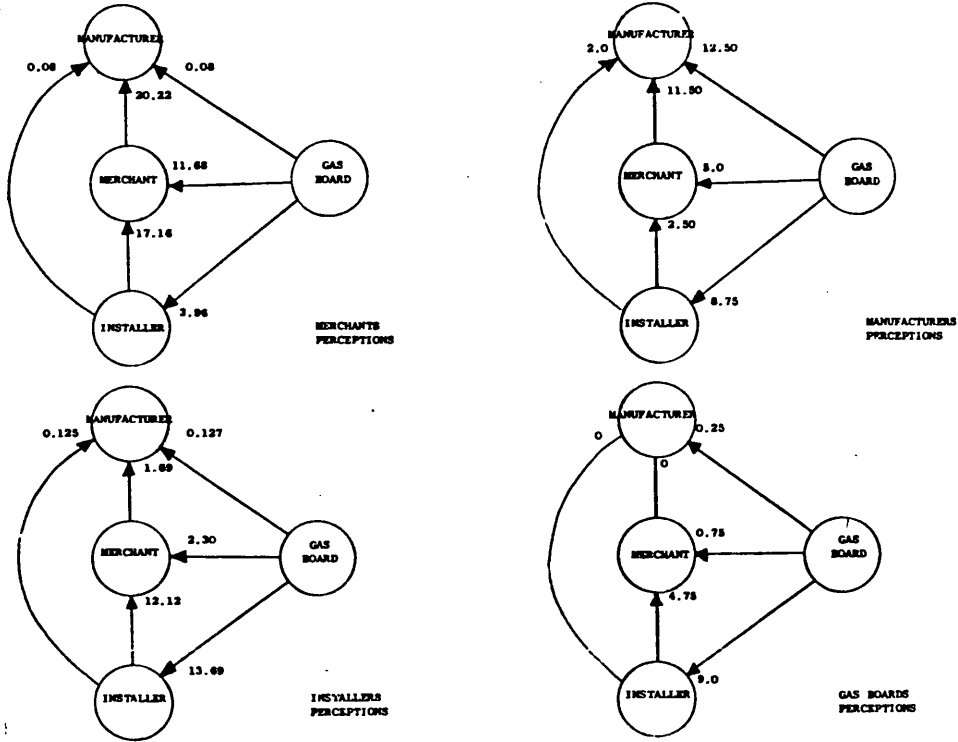-20 kPa at 1830 m
-30 kPa at 3020 m
-40 kPa at 4120 m

Figure 60

Suggested phial shape and method of filling for a production
gas filled F.F.D.

Figure 61

~2,500 Thermal Systems per wk

Harper Wyman Mercury F.F.D.	Teddington Mercury F.F.D.	T.I. Gas Controls Mercury F.F.D.	Concentric

Concentric: Mercury F.F.D. | Thermoelectric F.F.D.

~1,800 per wk.

~3,800 per wk.

~2,500 per wk.

~3,300 per wk.

~5,150 per wk.

COOKER O.E.M.'S

	TRADE NAMES	NO. SALES
Thorn Gas Appliances	Main, Parkinson Cowan	255,000
T.I.	New World	120,000
Glynwed	Flavel	64,000
Valor Co Ltd	Valor	64,000
Cannon Ind	Cannon	53,000
The Carron Co	Carron	19,000
1977	TOTAL SALES	575,000

Spares

Exports 15,000

Other retailers 8.6% sales

Imports ~5,000

B.Gas 91.4% sales

The market channel for domestic cooker F.F.D.s (1977).
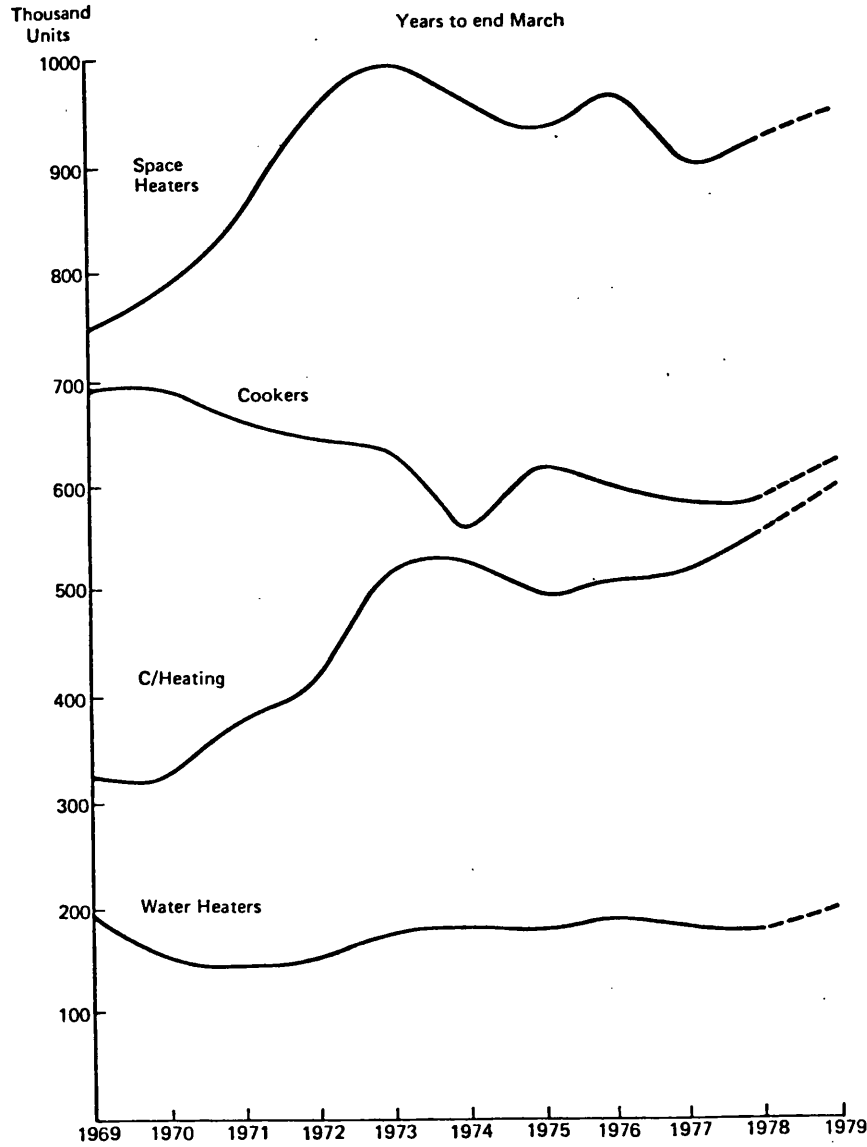Taken from (24) and (69).

Figure 62

Net total-power perceptions for the gas central heating
channel.
Taken from Ford (68).

Figure 63

The total annual sales for different gas appliances in the
United Kingdom.
Taken from the Monopolies and Mergers Commission report (69).