DESIGN OF AN EXPERIMENT
TO INVESTIGATE
SUPERHEAT EFFECT ON GATE VELOCITIES

by

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CHAPTER I

THE PROBLEM

Although the metal casting industry is one of the basic metal working industries and originated around 4000 B.C., it has long been dependent upon craftmen's skill, and only in relatively recent history has scientific and engineering techniques been applied to the solution of foundry problems. Among the more recent developments in the foundry industry has been the carbon dioxide process for rapidly and economically hardening cores. The last decade has seen rapid progress in the development of new and improved casting methods and techniques. In a free competitive society, industry must constantly seek more economical procedures for the processing of individual designs. In the metal casting industry particularly, these economic gains and better product quality are most often realized through better production methods. The knowledge of the castability of any given alloy in specific environments is therefore essential. To illustrate, the casting of liquid steel requires a more erosion resistant mold cavity surface than the casting of a liquid aluminum-base alloy, since the steel is more dense than the aluminum.

The term castability is a very general one implying the ability of a metal to be poured free of defects; dimensional and otherwise. The velocity with which molten metal flows through gates into the mold cavity may cause turbulence, air entrapment, oxide inclusions, and sand erosion with consequent casting defects. The superheat at which a metal is poured in turn may influence the velocity through a gating system of a particular molding medium. By the same token, the configuration of a gating system for a constant metal composition, pouring temperature and molding medium will influence the metal's gate velocity.

The lack of any available published information on the "superheat effect on gate velocities" through pressurized and unpressurized gating systems in molds cured by the carbon-dioxide process motivated this author to make this investigation.

I. STATEMENT OF THE PROBLEM

The objectives of this investigation were:

1. To design an experiment which will determine the effect variable degrees superheat have on the gate velocities in molds made by the carbon-dioxide process. The parameters of the experiment were aluminum 12-percent silicon casting alloy, poured into two different gating systems, at three levels of superheat.

2. To design and implement the controls necessary to exclude the significant effect of other casting variables upon gate velocities.

3. To statistically design the experiment so that the degree of interaction, if any exists, between degrees superheat, and types of gating system can be ascertained.

4. To substantiate the hypothesis that the hydrodynamic law of continuity for the pressurized flow of fluids in pipes is paralled by the flow of molten metal through pressurized gating systems in sand molds, i.e. ($Q = A_1V_1 = A_2V_2$).

II. IMPORTANCE OF THE STUDY

In reviewing the literature on Foundry Engineering and results of the experimental work that have been documented, it was a common experience to find a wide variety in testing techniques, frequent lack of complete data covering all the test conditions, various methods of interpretations and consequent difficulty in correlating one set of tests with another. The lack of completeness and uniformity in reporting data has restricted the investigators in making specific comparisons. The wide divergence in testing methods and criteria has lessened the usefulness of a large volume of experimental results in foundry engineering.

A considerable amount of variation is typical of observations made in foundry engineering research. Some of the variation is caused by the method of experimentation, variation in material composition etc. The use of statistical techniques helps to correlate the contribution of different sources of variation in a set of data. Therefore, it would seem desirable to present a statistical design of an experiment for making statistical analysis of temperature, pressure and gate effect on gate velocities.

III. SUMMARY OF RESULTS

For the pressurized (Gating Ratio 4.92:2:1) and unpressurized (Gating Ratio 1:3.33:1.67) gating systems (for details see figs. 7, 8, 9, 10), with two 3 in. long rectangular gates (Gate one: 3 5/8" from the sprue, area 1/8 in.^{2}, Gate two: 7 1/8 in. from sprue, area

17/128 in.^{2}), spaced 3 1/2 in. apart, the results of superheat (100-300°F.) effect on gate velocities of aluminum 12-percent silicon alloy in CO_2 molds, were analyzed statistically and show that:

1. Remelting of metal charge (new, first, second, and third remelts) has no effect on the velocities of aluminum - 12 percent silicon alloy through either gates in pressurized and unpressurized gating systems in CO_2 molds.

2. Pressurized and unpressurized gating systems have significant effect on velocities of aluminum 12-percent silicon through both gates in CO_2 molds. The pressurized system has higher gate velocities than the unpressurized system. The average increase in gate velocities of pressurized system is 1.249 ft./sec. with a standard deviation (deviations of the observations from the mean) of .1373 ft./sec.

3. Different degrees of superheat (100-300°F.) have no significant effect on velocities of aluminum 12-percent silicon through either gate in pressurized and unpressurized gating systems in CO_2 molds.

4. The position of gates has a highly significant effect on gate velocities of aluminum - 12 percent silicon, through each gate in pressurized and unpressurized gating systems in CO_2 molds. Gate farther from the sprue (Gate two) has higher velocity than the gate near the sprue (Gate one). The average increase in velocity is .295 ft./sec. with a standard deviation (deviation of the observations from the mean) of .0368 ft./sec.

5. There is no interaction effects (additional effect due to the combined influence)of (i) Pressure and superheat, (ii) superheat and gates, (iii) Gates and pressure, and (iv) Pressure, superheat, and

gates, on velocities of aluminum- 12 percent silicon through both gates in pressurized and unpressurized gating systems in CO_2 molds. That is, all the three variables (pressure, superheat, and gates) are independent of each other.

CHAPTER II

FLOW IN GATING SYSTEMS

I. INTRODUCTION

Gates are channels through which molten metal flows to fill a mold cavity. Their type and nomenclature depend upon the function they are designed to perform. Horizontal gating systems have received far more attention of the research workers than any other kind. They consist of all or several of the following components (see fig. 1): pouring basin, sprue, sprue base, runner, dross-trap and ingates. Each of these will be considered separately. The functioning of an individual component of a gating system is partly dependent upon the preceeding and subsequent sections; it is therefore, impossible to divide the system into a number of unrelated components, and the discussion of a particular part necessarily involves other parts and the system as a whole[42].

II. THE POURING BASIN AS A PART OF THE SYSTEM

A. Introduction

Although pouring basins have been used in gating practice to introduce the metal into the sprue, they are in any case a necessity when large castings are made. The pouring cup; however, is of further importance in that it is the element in a gating system which determines the

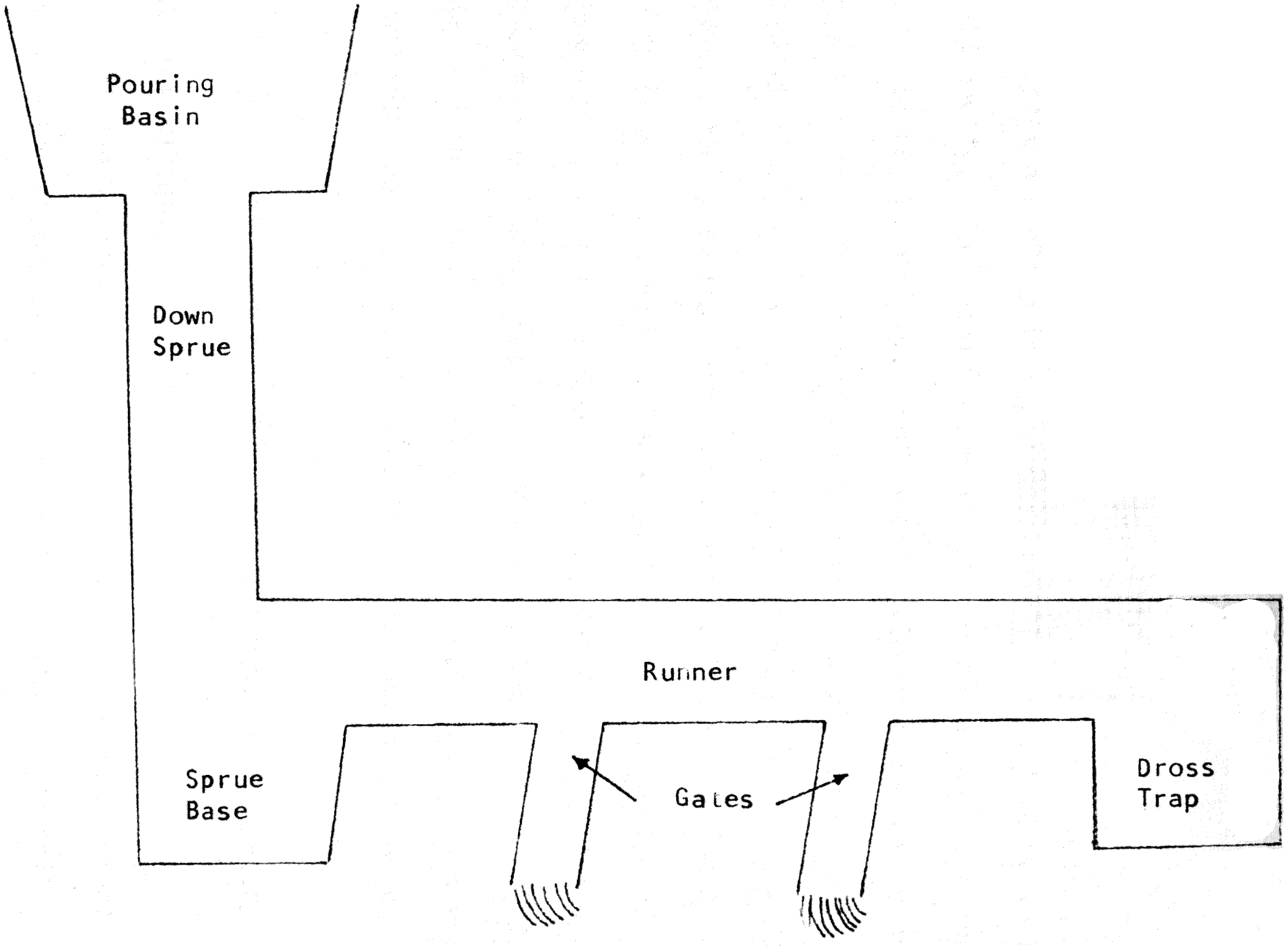


Fig. 1

Horizontal Gating System

maximum volume rate at which liquid metal may be introduced into the casting. Depending on the design of the remainder of the gating system, this maximum amount, or something less, may actually be delivered to the mold cavity. A flat-bottom pouring cup is essential to provide for the pressure condition required for optimum performance, cone shaped cups create a vortex condition which hinders metal flow.

"If the height of the metal in the pouring cup is increased, both flow velocity and volume rates of flow increases"[25].

B. Review of Previous Work

Using parallel (straight-sided) and tapered sprues Richins and Wetmore[39,40] studied the flow of aluminum. The exit area was equal to 0.39 in.^{2} in this investigation. Other factors considered with respect to sprue entrance were:

(a) Extension of the sprue
(b) Small funnel cut in mold
(c) Larger funnel cut in mold
(d) A pouring basin typical of that used industrially
(e) A similar, but larger, basin containing a 3-in. deep well
(f) A rectangular basin with heavily tapered sides
(g) A basin similar to (d) above, but of twice the length

They found that sprue entrances of types (a) and (b) were unsatisfactory, the flow rates of metal through the sprue being erratic and much dross being washed down the sprue. Type (c) gave a constant rate of flow with the parallel sprue, but was less satisfactory with the tapered sprue because of the higher pouring rate. Nevertheless, a constant flow rate was obtained with the tapered sprue if extreme care was taken in keeping the metal in pouring cup at the same level. The rate at which metal was delivered by the sprue was found to be constant with all the pouring basins (d) through (g) and to be independent of the volume (diameter or surface area wise) of the basin.

Richins and Wetmore[39] also examined the effect of radiusing the orifice in the base of the pouring basin through which the metal entered the sprue, and found that the rate of flow increased as the radius was increased up to an optimum value of 1 1/4 in. (for a range of 0 - 1 1/2" diameters).

Richins and Wetmore conclude that the shape of the pouring basin is immaterial, provided that its volume is sufficient (so that metal does not enter the sprue entrance directly) to permit easy operator-control and that the sprue entrance hole is adequately radiused.

Swift and his colleagues[45,46], showed that in the absence of a proper pouring basin, or if when using a basin the stream of liquid from the ladle were directed straight on the sprue entrance, much air was entrained in the stream and was carried down the sprue. They pointed out that such entrainment would cause drossy castings unless the entrained air were able to escape before reaching the mold cavity.

Swift[45] was also able to show that air entrapment occurred as the result of vortex formation if the pouring basin was not kept sufficiently full. (For details see Table for effect of sprue and pouring basin design on head required to avoid Vortex formation[45]). Furthermore, if a sharp sprue entrance were used, the flowing fluid separated from the sprue wall just below the entrance on the side nearest the pouring stream, forming an air pocket there (low pressure area). This air pocket gradually disintegrated, thus continually admixing air with the stream of liquid. This air pocket was almost entirely eliminated by using tapered sprues having their entrance radiused about 1 in. Radiusing the sprue entrance also increased the depth of liquid in the pouring box necessary to prevent vortex formation.

Swift[45] also concludes from his experiments with water models that the pouring basin should be filled as quickly as possible so that the minimum head is quickly reached (this is in any case desirable in order to fill the gating system as rapidly as can be done, and hence, to minimize air entrapment in other parts of the system). For the same reason he suggests that the sprue should be as short and of as small capacity as is reasonably possible. Swift also recommends the use of a stopper in the sprue entrance or a gate in the basin, which is removed when the required head of metal has been built up. Swift stresses the importance of a short and coherent pouring stream to minimize splashing and resulting air entrainment in the pouring basin.

The investigations of Richins and Wetmore[39,40] and of Swift and his colleagues[45,46] are in excellent agreement. These two studies form a good example of the complementary value of investigations using liquid metals and water models. The former provides quantitative information on the flow of the metal as well as permitting some observations on a situation and the production of dross, and the latter yielding valuable information on gas entrainment.

C. Summary

The above results provide adequate data for the construction and use of pouring basins which should conform to the following principles:

1. The basin should be large enough, so that the kinetic energy of the metal being poured is largely dissipated before it enters the sprue, and to permit easy control of the pouring stream without undue splashing.

2. The basin should be deep enough to enable the metal level to be held at a height sufficient to prevent vortex formation (about 2 in., see Table given by Swift[45]).

3. The length and breadth of the basin should be the minimum consistent with (1).

4. The orifice should be well radiused (see graph of Radius Vs. Flow Rate[45]).

5. The metal should be poured steadily, the pouring lip of the ladle being kept as close as possible to the basin.

In addition, when it is desirable to minimize agitation of the metal and the entrainment of air, the sprue should be of minimum height (see Table given by Swift[45]) and capacity consistent with other factors, a pouring basin stopper or a fusible plug at the entrance or exit of the sprue should be used.

III. THE SPRUE AS A PART OF THE SYSTEM

A. Introduction

The sprue is a common source of dross inclusions and entrained air, largely because the use of too large a cross section or too slow a pouring rate allows metal to fall freely at a high velocity and splash at the bottom of the sprue. Even if the pouring rate is high enough to enable the entrance to a parallel sprue to be filled, the stream of metal contracts and separates from the mold wall as it gains speed in falling, and splashing still occurs. This leads to aspiration and entrainment of mold gases, reduced volume of flow, and severe agitation at the base of the sprue.

Choking the base, if severe enough to keep the sprue full, avoids the worst defects arising from faulty design, but the sharp reduction in cross-section itself causes turbulence and local erosion due to high metal velocity. Experimental observations suggests that drossing and other effects at the bottom of the sprue are best avoided by greatly enlarging the cross-section of the base to reduce the velocity of the metal[13,15,39,45,46].

"The effect of sprue height on the flow of metal in a gating system is highly dependent on conditions which exist at the turn into the runner. This becomes evident by considering first the effects of sprue height in the absence of a turn; i.e., the addition to the pouring cup of a sprue of uniform cross-section and with an open end.

In the absence of a turn, the flow rate and velocity of metal falling from the cup through a given distance is the same as free fall through the atmosphere, i.e., as if the sprue were not present. This is due to the fact that the acceleration caused by gravity produces increased velocity of metal with increasing distance from the cup opening. Since the volume of flow is constant, the stream diameter must contract, thus providing for free fall within the non-tapered sprue.

The presence of turn at the base impedes flow and results in "piling up" of the metal so as to develop a pressure zone. The pressure developed at the turn determines the rate of flow from the sprue to the runner. The effective head at the turn increases with increase in potential head only to the point that the maximum rate of flow from the cup to sprue becomes equal to the rate of delivery from sprue to runner. When the pressure in the sprue is increased (by increasing sprue height) to a point such that the sprue delivers metal to the runner at a rate equal to the rate at which the cup can deliver metal to the sprue, further filling of sprue becomes impossible and a contraction region remains beneath the cup opening. This prevents further appreciable increase in the sprue head since increasing sprue height past this point merely results in increasing the length of the contraction (free fall) region. The impact of the freely falling stream provides but a small increase in the effective head.

By raising the height of metal in the sprue cup it is possible to use higher heights of sprue and eliminate contraction region. This results in increased flow rates into the runner and mold cavity.

This method of increasing flow rates deserves consideration also from the fact that the elimination of contraction regions by increasing cup heights prevents aspiration of air and drossing. The approach of tapering the sprue which is commonly used to prevent the development of a contraction region likewise is effective in preventing drossing. The two methods differ in that the tapered sprue method relies on decreasing the rate of flow from sprue to runner while the cup height method relies on increasing the rate of flow from cup to sprue. Depending on the gating problem, one or the other may be of advantage."[25]

B. Review of Previous Work

The work on the subject of sprues may be conveniently divided into that dealing with flow rates and that concerned with aspiration and other features of the flow.

(a) Flow rates in Sprues

(i) Parallel sprues:

A number of workers have examined the relations between the total head and the rate of flow through parallel sprues. Richins and Wetmore[39,40] comment that the flow through parallel sprues is always "entrance-controlled" (i.e., the rate of flow is limited by the diameter of the sprue entrance). They, therefore, suggest that the rate of flow through these sprues can be accurately computed from the head in pouring basin and the entrance area only, thus implying that the flow rate is independent of sprue height. This appears to be nearly true for the round sprues, but does not apply to the other sprues in which the flow rates were substantially less than predicted from the entrance area and pouring-basin head.

The suggestion made by Richins and Wetmore[39] has been confirmed experimentally by Mezoff and Elliott[14] working with magnesium, and by Johnson, Bishop and Pellini[28], working with steel. Martin[33] discusses the results of Ohira, a Japanese who found that the rate of flow increases with the sprue height up to a limiting height of 23.6 in. From the information available on Ohira's work Martin suggests that the apparent effect of sprue height may have resulted from failure to keep the pouring basin full in the case of castings made with the shorter sprue.

Although the rate of flow through parallel sprues is apparently independent of sprue height, the terminal velocity reached by the stream at the bottom of the sprue is markedly affected by sprue height, as is shown by the results obtained by Johnson, Bishop and Pellini[28].

The highest flow rates were obtained from round sprues and the increase in the perimeter to area ratio of the sprue cross-section decreases the rate of flow. This effect is attributed by all workers to increased wall frictional resistance. Swift, Jackson, and Eastwood[46], in experiments with water models, have also demonstrated the marked effect of sprue-wall surface area.

Johnson, Bishop and Pellini[28] showed that the presence of a runner profoundly affects the working of parallel sprues. The influence of sprue height and runner length was somewhat different in "equal-area", i.e. sprue and runner of the same diameter and "reduced-area", i.e.

runner diameter less than sprue. When both runner and sprue were short, velocities in the two types of systems were similar, since the sprue was completely filled and the head at the bend was the same in both cases. Lengthening the runner caused a larger velocity decrease in the small-diameter runner because of the greater frictional effects. The sprue in the "equal-area" system was only partially full, but that in the "reduced-area" system was completely full owing to the choking effect of the smaller runner. Hence, a greater head was present at the runner entrance of the latter system, with the result that velocities were greater than in the corresponding equal-area systems.

Robertson and Hardy[41] found that the flow rate was independent of sprue height and runner length.

(ii) Tapered Sprues:

Richins and Wetmore[39,40], in common with other workers, suggest that most of the faults of parallel sprues may be overcome by the use of sprues tapered towards the lower end in such a way that the decrease in cross-sectional area produced by the taper exactly compensates for the decrease produced in the cross-sectional area of the falling stream of liquid metal by the increase in velocity. In mathematical terms, the shape of the sprue is determined by the equation:

$$\frac{A_1}{A_2} = \frac{Z_2}{Z_1} \qquad 3$$

where A_1 = area of sprue entrance
A_2 = area at any other location in sprue
Z_1 = distance from top of the pouring basin to the location of A_2

Z_2 = level of the pouring-basin above the sprue entrance

It follows that the cross-sectional area of the sprue at any level must be inversely proportional to the square root of the vertical distance of that level below the liquid surface in the pouring basin. This implies that the vertical profile of the sprue should be a smooth parabolic curve, but Richins and Wetmore[39] suggest that for practical purposes it is sufficient merely to fix the cross-sectional areas of the top and bottom of the sprue by means of equation (1) and to draw a straight taper between these two areas. Richins and Wetmore[39] suggests that the entrance area may be made slightly greater than the calculated value, to err on the safe side.

Richins and Wetmore[39] pointed out that the tapered-slot sprue (rectangular cross-section) was exit-controlled (i.e. the sprue is full) over the full range of heads investigated. The other tapered sprues were exit-controlled only when the total head exceeded about 17 in. It is clear, therefore, that an adequate head must exist in the pouring basin if the sprue is to remain full. Possibly the failure of most of the tapered sprues to run full under low heads is connected with vortex formation.

This has been confirmed by Mezoff and Elliott[13] who showed that even a slight taper (3°) caused a marked dependence of flow rate on sprue height, whereas, the rate of flow from similar parallel sprues was independent of sprue height. This dependence was also shown by Swift, Jackson, and Eastwood[46] in experiments with water models.

Mezoff and Elliott pointed out that in tapered sprues the effective head is the sum of the head in the pouring basin and the sprue height, thus accounting for the marked dependence of the flow rate on sprue height.

Swift[45] points out that tapering enables the height of the sprue to be reduced without any reduction in flow rate. This technique is advantageous in that any decrease in sprue height results in lower velocities of flow at the sprue base.

Mezoff and Elliott[13] and Swift[45,46] have shown that use of a reverse taper (big-end down) produces a substantial increase in flow rate, presumably because of the absence of wall friction. Sprues of this kind, are likely to be unsatisfactory because of the danger of the gas entrainment.

(iii) The Effect of Pouring Temperature:

Robertson and Hardy[41] have concluded from experiments with copper-base alloys that the flow rate is sensibly independent of pouring temperature, provided that the superheat is sufficient to prevent freezing in the system. On the other hand, Mezoff and Elliott[13] carried out experiments with magnesium alloys which indicate that there is a rather ill-defined optimum temperature (about 790°C.) at which the rate of flow is maximum.

There is clearly insufficient information available on which to base a firm conclusion as to the effect of pouring temperature on the rate of flow in sprues and Gating systems.

(iv) Hydraulic Losses in Sprues:

It has been described that there is a loss of head at the entrance of the sprue which can be reduced by suitably radiusing the entrance. It is also clear that a further loss of head occurs during passage of the metal down the sprue as the result of wall friction.

Several workers[13,39] have confirmed that radiusing the entrance substantially increases the rate of flow.

Mezoff and Elliott[13] in experiments with parallel sprues demonstrated that the amount of metal passed by the sprue was not directly proportional to the cross-sectional area of the sprue, but that the efficiency of the sprues decreased with increase in area.

On the other hand, Johnson, Bishop and Pellini[28] indicates that the sprue entrance loss decreases with increase in diameter. This may possibly be due to the fact that the sprues used by Johnson, Bishop and Pellini had 1/2 in. radii at their entrances, whereas those of Mezoff and Elliott had sharp entrances.

Richins and Wetmore[39,40] have studied wall frictional losses in sprues in a quantitative manner. They made measurements of both the entrance loss and the total loss in tapered sprues, and were thus able to deduce[40] hydraulic loss coefficients for the wall frictional loss.

(b) Aspiration and other Features of Flow in Sprues

Elliott and Mezoff[13] showed that:

1. The volume of air aspirated increases with permeability, at least up to a certain point. (see graph on Air aspiration Vs. Permeability[13])

2. Large (no specific data given) head in the basin increases aspiration.

3. Considerable aspiration occurred with parallel or reversed-taper (big-end down) sprue.

4. Aspiration was absent in tapered sprue (2 in. diam. at top and 3/4 in. diam. at bottom) and parallel sprue (1 1/2 in. diam.) constricted at the bottom

5. Little aspiration occurred with slot sprues of 2 x 1/2 in. cross-section and none in 2 x 3/8 in. cross-section. (No quantitative results were obtained, see table 1[13]).

6. Absence of aspiration was accomplished by a positive pressure within the manifold; this positive pressure was ascribed to expansion of mold gases on heating.

Swift showed that:

1. Aspiration always occurred when the pressure at a sprue-wall hole was negative and that the rate of aspiration was proportional to this negative pressure.

2. All parallel sprues aspirated air to some extent. The reverse-tapered sprue aspirated substantial volume of air.

3. The slightly tapered sprue (ratio top/bottom area = 1.5) aspirated some air, but the other tapered sprues (top/bottom area = 2 & 3) did not aspirate any significant amount of air.

4. Aspiration just below (this was not measured) the sprue entrance increased rapidly with increase in velocity, the velocity at this point is largely determined by the head in the pouring basin.

5. Aspiration was greatest near (this was not measured) the top of the sprue.

Johnson, Baker and Pellini[24] consider that if the head in the pouring basin is insufficient and the top of the sprue is not filled, true aspiration will not occur, since the pressure in the sprue will be equalized by that of the atmosphere. They suggest that in these circumstances entrainment of gas results from the severe agitation caused by the metal stream striking the sprue walls on its passage downwards.

C. Summary

The most important outcome of the experimental work described is the evident superiority of the tapered over the parallel sprue. This superiority rests on:

1. Tapered sprues (taper according to $\frac{A_1}{A_2} = \frac{Z_2}{Z_1}$[3]) are unlikely to cause dross or porosity in the casting because flow in them is quiet and they do not aspirate mold gases to any appreciable extent. On the other hand, flow in parallel sprues appears generally to be agitated, and these sprues aspirate considerable amounts of gas, unless the system is heavily choked at the runners or gates.

2. The effective head in parallel sprues may vary between that present in pouring basin and a value approaching the head represented by the sum of the height of the sprue and the height of the metal in the basin.

On the other hand, the effective head in tapered sprues is always the sum of the pouring-basin head and the height of the sprue, so that flow rates in these sprues may readily be calculated.

3. A tapered sprue has a smaller volume for a given flow rate, so that the casting yield may be improved by using a tapered sprue.

Other points emerging from the work described are:

(i) The desirability of low velocities at the sprue base.

(ii) The desirability of an adequate head (more than that required to prevent vortex formation, as per table given by Swift, Jackson, and Eastwood[46]) in the pouring basin.

(iii) A radiused sprue entrance (see plot of Radius Vs. Flow rate and Discharge coefficient given by Richins and Wetmore[39]).

IV. SPRUE BASE AS A PART OF THE SYSTEM

A. Introduction

The stream of metal issuing from the end of the sprue in a gating system is traveling downwards with a high velocity. This stream is diverted through right angle (90°) in the sprue base into one or more runners of greater or less cross-sections than that of the sprue exit.

intense metal agitation and considerable mold gas may occur in the sprue base, due to these abrupt changes in the velocity, direction and cross-section. Eastwood[11] suggests that the metal should enter the mold cavity at one-quarter to one sixth of the velocity in the sprue base.

Thus, the sprue base should allow the change in direction and reduction in velocity of the stream to take place with little agitation and erosion. Also, it should be small enough to be filled without damaging a large volume of metal by entrainment of the displaced air.

B. Review of Previous Work

Richins and Wetmore[39] found that when (tapered) sprue exit and runner are of equal area the flow is smooth in all the six bases they examined. But when the sprue exit area was half that of the runner, the flow from all the sprue bases was agitated with the exception of radius bend and surge sump (similar to rectangular sump) type of sprue bases. The flow was smooth in surge sump and filled the runner.

Richins and Wetmore[39] were able to compute the head-loss coefficients. They state that for 13 in. height parallel sprues, the flow rate is governed by the sprue entrance and is independent of the type of sprue base used. Johnson, Bishop and Pellini[28] suggest that this depends on whether the sprue is full or not.

These workers showed that when the sprue base divides the metal stream into two runners, reasonably equal division could be obtained if the total runner area is equal to or slightly greater than double the sprue exit area.

Swift, Jackson, and Eastwood[46] used a "tee" junction at the bottom of the sprue, and found that at the beginning of the pouring, an air pocket is formed beneath the sprue which slowly disintegrates causing entrainment of air bubbles in the stream. Another design with sprue end projected well below the runner, also suffered from air entrapment. A third design of sprue base consisted of a streamlined (to avoid right-angle change in direction) tee junction beneath the sprue exit. This was found satisfactory as it eliminated the air pocket and air entrainment and also increased rate of flow.

Grube and Eastwood[19] concluded that an enlargement in the runner below the sprue exit prevents aspiration but does not eliminate trapped air. Reduction in the velocity of flow by the use of inserts to enlarge the runner caused rapid elimination of the trapped air, but these authors state that these inserts are suitable to one particular gating system used and usually unsuitable to others. They, therefore, state that the use of inserts is not a general solution to the problem.

Grube, Kura, and Jackson[20] examined three types of sprue bases: tee base, enlargement base, and well base. Their results showed with:
<u>Tee base</u>: A severe aspiration and agitation. Long periods of time are needed to wash the trapped air out of the system.
<u>Enlargement base</u>: Much less agitation and aspiration and trapped air washed away quickly. More aspiration occurs with wide shallow runners (width range 1-2 in.; depth range 3/4-1/2 in.) as compared to narrow deep ones (width range 3/4-1 1/2 in.; depth range 1-2 in.).

Well-base: The well-base area should be about five times that of the sprue exit area and well depth should be approximately equal to that of the runner. The advantages with this kind of sprue-base are: (1) it prevents aspiration, (2) reduces clean up time to reasonably low value, and (3) functions in a wide range of runner geometrics and sprue sizes.

C. Summary

The above discussion of previous work shows that three types of sprue base behave in a satisfactory manner; (1) the streamlined base like the radius bend used by Richins and Wetmore[39] and some (streamlined tee base and streamlined with enlargement) of the bases studied by Eastwood and co-workers[19,46], (2) the enlargement base studied by Eastwood and co-workers[19,20], and (3) the surge sump investigated by Richins and Wetmore[39] and the closely similar well base of Grube, Kura and Jackson[20].

Streamlined bases are desirable from the point of view of metal flow and aspiration, but have the disadvantage that they do little to absorb the momentum of the metal. Also their use requires a core and is therefore unlikely to be popular in industry. It seems therefore, that the surge sump and enlargement bases are the most useful sprue bases. It may be noted that the use of the enlargement base is restricted to narrow, deep runners and the relatively large volume of the surge sump will decrease the casting yield. It seems, therefore, that the choice between them will be governed by the geometry of the runner and by economic considerations.

Hydraulic theory suggests that sprue bases with gradual enlargement from sprue exit to that of the runner might yield very satisfactory results.

V. RUNNER AS A PART OF THE SYSTEM

A. Introduction

In the distribution stage of metal flow from the point it enters the runner till it flows into the mold cavity, the energy of the metal stream is maximum on entry into the runner. From here onward the distribution of metal into the mold cavity depends on the particular type of energy available (pressure or kinetic) and the proper use of it. The energy is primarily in the form of pressure for a runner which flows full while it is entirely kinetic for a runner which remains partially filled.

It is therefore, important to determine whether the runner flows full or in a partially empty condition.

Reducing the area of the runner to less than that of the sprue exit reduces the flow rate, and makes both sprue and runner full and pressurized. Also, flow velocity from such runner is directly related to sprue height since the contraction region in the sprue is eliminated due to the choke condition at the turn[25].

"If the cross-section of the runner near the sprue base is too large (larger than sprue exit) the stream of the metal leaving the sprue incompletely fills the runner and oxidation of the top surface of the stream can readily occur, possibly accompanied by agitation, local aspiration and entrainment of air. This tendency is accentuated by a badly designed sprue base, e.g. one excessively choked which delivers metal at too great a velocity."[42]

In case of equal area (sprue exit and runner of same area) system, Johnson, Bishop and Pellini[25,28] found that in 1-in. diameter sprue-runner systems with runners 15 in. in length no portion of the runner fills completely. With the runner length greater than 15 in. the runner becomes almost completely full, with consequent development of a back pressure which serves to reduce the amount of metal entering the runner from the sprue. However, as the metal travels along the runner, frictional effects cause velocity to continually decrease. Since the rate of flow through the runner remains constant, a decrease in velocity may eventually fill the cross-section of the runner. This means that the runner becomes increasingly more full as the distance from the sprue is increased.

Thus, the use of a long runner, which steadily chokes the stream, eliminates agitated flow of oxidized metal into the mold cavity. Gating-off (or gates at) the top surface of the runner also results in its rapid filling. Gating-off the bottom of the runner is said[11] to prevent oxide on the surface of the stream from entering the mold cavity, even if the runner is only partly filled.

However, whatever method is used to keep the runner full, some of the inclusions introduced near the sprue base are likely to remain. Even a well-designed sprue must therefore, be connected with a runner of correct dimensions to avoid completely the effects of agitation.

The cross-section of the runner must be specified in relation to sprue and gates size. The relative sizes of these components are discussed under "Gating-ratio". Probably the most satisfactory shape of the runner is an inverse-taper. Sharp bends and sudden changes in cross-section should be avoided to avoid the formation of "dead" pockets which consequently results in agitation and entrainment of air.

B. Review of Previous Work

Richins and Wetmore[39] found that in systems using tapered sprues the flow rate decreased slowly with increasing length of the runner. With small runners the rate of decrease was greatest. These authors stress that smooth flow into the mold as a result of the use of long runner does not indicate that gas entrainment and dross formation has not damaged the metal near the entrance of the runner.

Johnson, Bishop and Pellini[26] found that the distance from the sprue base at which the runner became full increased with (1) the ratio of runner area to sprue exit area and (2) the velocity with which the metal entered the runner.

In the view of Swift, Jackson, and Eastwood[46] the runner area (in unpressurized system) should be increased gradually from that of the sprue exit to a value about four times greater to decrease flow rate and turbulence. They also suggest that abrupt changes in cross-sectional area of the runner should be avoided to prevent separation and gas entrainment.

Experiments by Johnson, Bishop and Pellini[26] employing parallel sprues demonstrated that if the runner area is smaller than the sprue exit area, the effective head and flow rate are likely to increase. Whereas, a decrease in flow rate could be expected when tapered sprues are used.

Experiments by Richins and Wetmore[39] showed the influence of choking effect produced in the runner on the static pressure in the system. High pressure develops throughout the system when a substantial choking effect is produced. Conversely, when the runner does not choke the sprue, pressures everywhere are relatively low and atmospheric or subatmospheric in the sprue itself. When tapered sprues were used, positive pressures were recorded everywhere in the system.

Berger and Locke[4] states that runner friction is unimportant unless the ratio of length to diameter of the runner exceeds 16.

Swift, Jackson and Eastwood[46] studied with water models the phenomena occurring at runner bends. In case of sharp cornered bends, they showed that separation and aspiration occurs at the inside vertical wall of the runner, downstream from the corner. They found that the volume of air aspirated increases very rapidly with increase in the flow rate. Their results indicate that unless the flow velocity is very low, runner bends should always be streamlined (to avoid sharp change in direction).

VI. DROSS TRAP AS A PART OF THE SYSTEM

A. Introduction

The two kinds of dross trap are:

1. Those which prevent first damaged metal from entering into the mold cavity;

2. Those which filters or otherwise cleans all the metal passing through the system.

First kind usually consists of a blind end fitted to the runner, beyond the final gate and terminating into a sump. The first poured metal flows down the runner, its momentum carrying it into the sump before any metal enters the gate. The metal enters the gate only when the sump is filled and back-pressure is developed. Thus, the damaged first-poured metal containing dross and entrained air is kept out of the mold cavity. Most workers, who studied gating of castings recommend the use of this kind of dross trap in all gating systems. Attempt has not been made to determine its optimum design, which is important as the sump represents loss of metal.

Dross trap which filters or cleans dross from the metal stream usually consists of a (i) perforated steel or mesh screen, (ii) a strainer core (a biscuit shaped core), (iii) a serrated top surface of the runner, shaped so that the dross readily floats into the teeth but cannot afterwards escape. They are placed near the sprue base or in the runner, so that all metal must pass through. Besides cleaning the dross, the most beneficial effect is the choking action they produce which ensures that the sprue system is filled. As the holes in many forms of filters are too large to hold back all the harmful dross particles, it is doubtful that they are ever more effective than a well designed running system. This kind of trap may increase the casting yield by simplifying the running system and can also be used to facilitate casting removal.

B. Review of Previous Work

Elliott and Mazoff[13] concluded that screens not only cleans dross but also reduces aspiration and agitation in metal by choking the flow. This also has been suggested by Swift, Jackson, and Eastwood[46].

Grube, Kura, and Jackson[20] concluded that screens are valuable for correcting poor gating practice, but they do not consider screens as a substitute for good gating practice.

Richins[38] states that screens are valuable and that when they are properly used it is permissable to deviate from some of the principles of good gating practice. He also considers that a screen reduces the agitation present in the sprue and sprue base.

Swift[45] states that screens are unlikely to prevent all oxide-coated bubbles from reaching mold cavity, and that dispersion of bubbles by the screen might result in greater production of oxide.

Strainer cores may be expected to have a greater choking effect owing to smaller total hole area and be less efficient in removal of dross and entrained air because of relatively large holes. Tedds[48] and Elliott and Mezoff[13] agrees that a steel-wool strainer placed in pouring basin does not appreciably reduce the amount of dross passing into the casting.

McDonald concluded that strainer cores are valuable means of controlling pouring rates and diminishing flow velocities, but have negligible filtering effect.

VII. INGATES AND GATING RATIO

A. Ingates

(a) Flow through Ingates:

A pressurized runner develops flow from all ingates by producing pressure on all ingates. The runner is pressurized either by reducing its area to less than that of the sprue base or by choking at the ingates. A non-pressurized runner is larger in cross-section than sprue base and depends on the proper use of kinetic energy to achieve uniform distribution of liquid which is moving in a straight line path to avoid entering lateral ingates.

In a pressurized system, with gates of equal area, equal volume of flow at the same velocity occurs from each ingate. This is because equal pressure is applied to the metal at each ingate opening. If one ingate is made larger or smaller than the others, the volume of flow from that ingate will increase or decrease in proportion to its size relative to the remaining gates. Though, the velocity does not theoretically change since the pressure remains unchanged.

The pressure head in the sprue and the total area of the ingate openings determines the total flow in a pressurized gating system.

The total head is equal to the height of the metal in the runner to the metal level in the pouring cup if the sprue is completely filled or to the height of the metal in the sprue just below the point of stream contraction, if a contraction region exists. Thus, in practice it is possible to increase the rate of flow in a pressurized system by (i) increasing the number or size of the ingates and (ii) by increasing the height of the metal in the cup-sprue portion of the system.

Unpressurized gating systems distribute metal primarily by kinetic energy. The flow through the ingates is non-uniform and the ingate or ingates farthest from the sprue delivers most of the metal and at higher velocities. Generally the maximum velocity of flow in unpressurized system is less than that of the pressurized system.

Multiple-gate systems are often used to produce even temperature distribution in the casting[43]. It is difficult to achieve uniform flow through all the gates in a multiple-gate system, as the momentum of the metal carries most of it through the gates farthest from the sprue. Though too great a momentum may even cause the flow of the metal to be reversed through gates near the sprue. Various designs are developed which permit distributing metal through a multiple-gate system without the requirements of pressurization and consequent high velocities. "Observation of the performance of varied arrangements of gates indicates that uniform flow is encouraged by: (i) reducing the momentum of the stream by the employment of the enlarged runners, (ii) increasing the resistance to flow through the end gates by suitably reducing their cross-section and/or that of the runner, thus raising the pressure at the other gates, or (iii) distributing the momentum of the stream more evenly by varying the angles between the arms of the runner and the gates. The first two methods are the most generally applicable"[43].

Systems for casting dross-forming alloys are preferably gated near the base to prevent metal splashing into the mold cavity. As the mold fills, the back-pressure of the metal in it helps to keep the runners full. If the angle between the gate and the runner is sharp, agitation and entrapment of air is likely to occur near their junction. This may be greatly diminished by streamlining (to avoid right angle change in direction) the junction, and at the same time reducing the cross-section of the runner to avoid enlargement of the total cross-section of the channels.

B. Review of Previous Work

Swift, Jackson and Eastwood[46] in their experiments with water models showed in case of gates taken off at right angles to the runner that abrupt changes in direction at the junction of the gate and the runner, produced a strong tendency towards separation and air aspiration. This tendency increased considerably with large gates of total cross-sectional area two or more times that of the runner.

Eastwood[11] states two advantages of placing the gate in the cope and the runner in the drag. They are: (1) none of the gates pass metal until the runner is completely full. This means that dross formed in the initial part of the pouring may rise to the top of the runner and adhere to sand, allowing clean metal beneath it to run through the gates;

(2) a slight degree of pressurization is achieved without high velocities in the gates.

Johnson, Bishop and Pellini[26] showed that employing tapered gates (wide end attached to the casting) is useless, as the stream does not widen out enough to fill the end of the gate, owing to the jet effect.

Swift[45] proved by experiments with water models that with increase in velocity of the metal streams emerging from the gates, the amount of splashing in the mold cavity increases. This also increased the amount of gas trapped against the cope face of the mold cavity. He therefore, emphasized the desirability of low metal velocities and high permeability of the cope half of the mold.

Johnson, Bishop, and Pellini[27] distinguished between four types of agitation in mold cavity: (1) rolling, (2) swirling, (3) rocking, and (4) irregular. They consider that when the flow from the gates is more or less uniform rolling occurs, swirling results from non-uniform flow, intermittent discharge from the gates produces rocking, and irregular agitation occurs when the velocity of the metal entering the mold is high. In another study[26] these workers found that to ensure uniform flow from the gates, runner area equal to and preferably twice the gate area was necessary. They also found that greater uniformity of flow is achieved with the rectangular-section gates than any other gates. They consider this to be the result of their greater surface area and hence higher resistance to flow. They also found that increase in gate length (from 3 to 6 in., with diameter 1/2 in.) increased the resistance to flow, thereby causing more uniform flow.

Johnson, Baker and Pellini[24] show that uniform flow from different gates can be achieved in two ways: (1) by reducing the momentum of the stream to a low value by means of enlargements, which permits uniform flow without the generation of much pressure, (2) by pressurization, i.e. by increasing resistance to flow at ingates by suitable adjustments to the geometry of the system. Systems involving tapered runners and leading the gates off the top of the runner are good examples of it. This technique allows relatively high pressure to develop upstream causing the gates there to feed uniformly despite the momentum effects.

Johnson, Bishop and Pellini[25,28] showed that:

1. With the addition of a gate (3/4" or 1" diameter) to a 3-in. runner, the runner was partially filled, i.e. it did not pressurize the system and did not increase the velocity of flow, whereas

2. Addition of a gate (any size) to a 12-in. runner increased the velocity. The reason attached to this was greater effective head resulting from the back-pressure developed as a result of the increased resistance offered by the more complete filling of the runner.

3. In both cases reduction in the gate diameter resulted in decrease in the flow rate but increased the velocity of the issuing stream. This increase in velocity was in part due to increase in the effective head resulting from more complete filling of the sprue.

4. The total flow rate was slightly higher in the two gate system than in the single gate system.

5. In the four-gate system: (a) both the rate and velocity of flow

were greater in the end gates, as obtained by Johnson and Baker[29], (b) decreasing the gate diameters decreased the flow rate and increased the velocities; also reduced the discrepancy between the velocities and the flow rates through the individual gates.

Richins and Wetmore[39] investigated flows from different gates in a four-gate system and found that in general, the end gates passed the most metal. They state that the gates which passed the most metal were situated in regions where static pressures were highest. They also found that by placing the gates at the bottom of the runner, at angles other than 90° more equal flow is obtained.

Berger and Locke's[4] results, like those of Johnson, Bishop and Pellini[28], Richins and Wetmore[39], show that when all gates in a system have the same area the end gates pass the most metal. Like Johnson, Bishop and Pellini[28] they found that decreasing gate area improves the uniformity of flow from the different gates.

Swift's[45] results can be summarized as: (1) the end gates carry most metal in unpressurized systems, (2) uniformity of flow is improved by reducing flow rate, (3) the head in the pouring basin does not markedly affect the uniformity of flow, (4) placing constriction in the runner between gates improves the uniformity of flow, (5) the use of screens and well sprue bases favors uniformity of flow.

B. Gating Ratio

(a) Introduction and Importance:

The term "Gating Ratio" describes the relative cross-sectional areas of the components of a gating system. It is defined as the ratio of the sprue base area to total runner cross-sectional area to total gate area. All cross-sections measured perpendicular to the direction of flow.

In the pressurized system a back pressure is maintained on the gating system by a fluid-flow restriction at the gates. This requires that the total gate area be not greater than the area of the sprue base, e.g. in systems with gating ratios of 1:2:1 or 1:0.7:1.

In the unpressurized systems, the primary restriction to fluid flow is at or very near the sprue. Gating ratios such as 1:4:4 are used for this type of system.

This quantity is of great importance because, as explained above in the discussion of individual components of a gating system, the gating ratio determines: (1) the uniformity of flow in a multiple-gate system, (2) the degree of agitation, erosion and aspiration between the sprue and the casting, (3) the velocity at which the metal is delivered into the mold cavity and hence the extent of drossing and erosion there, and (4) the total rate of flow.

A general tendency is to use pressurized gating systems for casting ferrous metals and unpressurized systems for light-alloys.

Pressurized systems have the advantage of: (a) simplicity, (b) uniform flow, (c) a full system which minimizes dross formation. It has the disadvantage that high velocities in these systems increase the danger of gas aspiration and consequent dross formation. Also the high velocity at which the metal enters the mold cavity may cause severe agitation and mold erosion there.

Low velocity in unpressurized systems reduces the danger of gas aspiration, mold erosion and agitation in mold cavity. The disadvantages of these systems are: (i) the difficulty of obtaining uniform flow, (ii) possibility of incomplete filling of the system which may cause some dross formation, (iii) enlargement effects may lead to aspiration.

(b) Selection of Gating Ratio:

Chief factors for the selection of a system are: (1) the readiness with which the alloy being cast forms objectionable kinds of dross, (2) the danger of impingement against cores and the mold walls.

Evidence available does not seem to permit more than a rough choice to be made between the different gating rations suggested for pressurized and unpressurized systems. For pressurized systems Johnson and co-workers[26,27,28] suggests that the gating ratio should be 1 : > 1 : 1 for uniform flow and preferably 1 : 2 : 1.

It is even more difficult to select an optimum gating ratio for unpressurized systems. Most workers seem to take the view that the velocity of the liquid should be reduced between 4 and 6 times in passage from the sprue to the mold cavity. It must be realized that the larger this reduction, the more difficult does the design of the system become, if uniform flow is to be attained, and at the same time reduce aspiration due to enlargements of the system. According to Ruddle[42], if the velocity is retarded sufficiently in the sprue, much smaller sprue area: Gate area ratios, such as 1 : 2 or even 1 : 1 should suffice. Grube and Eastwood[19] consider that in unpressurized or slightly pressurized systems the gate and the runner areas should be equal. However, making the gate area slightly less than the runner pressurizes the runner to a small extent so gating ratios of 1 : 6 : 5 (or 1 : 2 : 1.6) might be suitable.

CHAPTER III

FLUID DYNAMICS OF METAL FLOW

I. THE NATURE OF THE FLOW

Two types of flow occurs (i) streamline or laminar and (ii) turbulent.

Laminar flow is characterized by a straight-line movement of the fluid particles in the direction of flow[1]; the velocity of the particles in the directions perpendicular to the direction of flow is therefore nil.

Turbulent flow is that type of flow in which the particles of fluid proceed in a very irregular manner back and forth across the stream as the whole mass of liquid moves along[45].

The existence in all fluids of two critical flow velocities has been established[23]. Below the "lower critical velocity" flow is invariably laminar and above the "upper critical velocity" it is turbulent; in the intermediate range flow may be either laminar or turbulent. In the absence of disturbances the velocity may be steadily increased up to the upper critical value before turbulence begins, whereas if disturbances are present, turbulent flow will be initiated just above the lower critical velocity. Disturbances capable of initiating turbulent flow may be caused by vibration, obstructions, abrupt changes in flow directions or channel dimensions, etc.; i.e. by failure to streamline the system. Once it is present, turbulence can be prevented only by reducing the velocity below the critical value. Although the lower critical value is sharply defined, the upper critical velocity is dependent upon the precautions taken to prevent disturbance of the flow.

A. Dynamical Similarity of Flow: Reynold's Number

Two kinds of forces are present in a flowing liquid[23]: Viscous forces which tend to promote laminar flow and inertia forces which promote turbulent flow. It, therefore follows that the character of flow of different liquids flowing in channels of different dimensions, ought to be the same provided that the ratio of inertia force to viscous force is identical in all cases.

This ratio is called the Reynold's number (N_R) and is defined as:

$$N_R = \frac{(\text{Vel. of Flow x Diam. of Flow Channel x Density of Fluid})}{\text{Viscosity of Fluid}}$$

(For a circular cross-section)

and

$$N_R = \frac{(\text{Vel. of Flow x } \frac{\text{4 x cross-sectional area}}{\text{Perimeter of cross-section}} \text{ x Density of Fluid}}{\text{Viscosity of Fluid}}$$

(For non-circular cross-section)

Thus, the nature of the flow of all fluids is the same at equal Reynold's Number. The lower critical velocity for flow in pipes has been found to correspond to N_R 2000 for all fluids; the upper critical velocity is generally held to correspond to N_R of 3000-4000.

It follows from above that a water model of a gating system should accurately reproduce the character of (steady-state) flow of a metal in the corresponding sand-molded gating system, provided that the Reynolds' numbers in the two cases are about equal. Reynold's number is dependent on the diameter of the flow channels and on the kinematic viscosity of the liquid, and it is therefore of interest to compare the kinematic viscosities of liquid metals with that of water and other fluids.

The kinematic viscosities of aluminum and magnesium are similar to that of water, and full-scale water models of gating system for these metals should therefore give actual reproduction of steady-state flow conditions in the actual gating systems.

The kinematic viscosities of heavier metals, are lower than that of water, and it may therefore be desirable to scale down the dimensions of the water model so as to make the Reynolds' number about equal in the model and in the actual gating system. Richins and Wetmore[39] have shown that the flow of liquid aluminum flowing turbulently in a closed duct is similar to that of water at the same Reynolds' number. Swift[45] has shown that the rates of flow of water, mercury and Wood's metal in a plastic model of a gating system are almost identical, provided that the flow is turbulent (i.e. $N_R > 2000$).

A possible cause of incompleteness in the analogy between the flow of water and liquid metal is the difference in surface tension. The surface tensions of liquid metals and alloys are substantially greater than that of water. Furthermore, the surfaces of many liquid metals are covered with a tenacious oxide skin which greatly increases the apparent surface tension of the metal. Difference in permeability between sand molds and plastic molds is another reason of incompleteness in this analogy.

These differences in surface tension should not greatly influence the analogy between the steady-state flow of water and of liquid metals, but may give rise to discrepancies where unsteady flow is concerned. Surface tension forces are small compared with the other forces operating in fluid flow, and effects of this kind are probably insignificant. Effect of the high surface tension of metals may be a reduction in splashing in the mold cavity and elsewhere as Swift[45] has pointed out. Other possible effects of high surface tension are a reduction in violent agitation and vortex formation and a smaller tendency of the flowing stream to entrain gas bubbles.

B. Turbulence in Gating Systems

"Turbulence relevant to the pouring of castings, in its broadest sense, can be considered any kind of fluid disturbance. There can be turbulence within the flow stream in the form of secondary irregular motions and velocity fluctuations superimposed on the principal or average flow. Turbulence in the body of a flowing stream of liquid light alloy may be violent enough to break up the enveloping oxide coating, and as a result allow more surface oxide to be formed. Also the oxide particles would tend to mix in the molten stream of metal and might be carried into the mold cavity to produce defects in the finished casting.

Waves, a possible second type of turbulence, will certainly exist in the mold during the pouring operations, but it is not likely that this type of disturbance will cause significant casting defects.

A third type of turbulence, splashing of a liquid metal in the mold could do considerable damage to the finished casting. The splashing of a liquid may be considered as the breaking up of a large mass of liquid into smaller masses with the creation of new surface.

A fourth type of turbulence which, like the third one, is probably of considerable importance consists of the aspiration of air or mold gases through permeable walls of gating channels and into the casting liquid. This would occur where the type of flow and channel design are such as to create a partial vacuum between the flow liquid and the channel wall.

In a gating system commonly used in practical foundry practice, bends, sharp corners, and abrupt changes in cross-sectional area in the flow channels can cause a trend toward more turbulence of all four types. The same geometric conditions could cause a splash of liquid metal, particularly in the case of any change in the direction of fluid flow. A typical example of an abrupt change in direction exists at the base of the sprue of a mold during the pouring operation. Generally, splashing is of considerable concern only at the beginning of the mold-filling operation"[45].

Calculations of Reynolds' number, using values of kinematic viscosity (taken from Ruddle, R. W.[42], Table II, p. 20), reveal the fact that the flow of metal in most practical gating systems is turbulent. Robertson and Hardy[41] measured the velocity of flow of gun-metal through gates of various sizes and found their measured rates to be ten times greater than the lower critical value. This leads to the conclusion that some turbulence is inevitable in all conventional gating systems. However, since perfectly clean castings can be made using gating systems in which the flow must be turbulent, it is clear that a certain amount of turbulence can be tolerated. Eastwood[10] has suggested that two types of turbulence may be recognized: (i) a harmful kind, so severe that the oxide skin round the periphery of flowing stream or on the surface of the metal in a mold cavity is broken - this leads to the formation of dross inclusions in casting; (ii) less severe turbulence which does not cause rupture of the oxide skin and is therefore harmless.

II. LAWS FOR RATES OF FLOW

A. Transient and Steady Flow

There are three stages in liquid flow. First, when the liquid enters a system of ducts or channels much agitation and splashing occurs, which become severe if there is any vertical drop in the system. The second stage occurs after the liquid has reached the exit of the system, when the ducts or channels tend to fill with liquid and agitation and splashing tend to die out, and the volume rate of flow tends to a constant value. In the third stage the flow is relatively steady and constant, provided the back-pressure produced does not alter.

This is important from the point of view of the gating system. A considerable amount of air or gas initially present in the ducts is liable to be entrained in the stream during the first two stages of flow.

The rates and velocities of flow during the first two (transient) stages are not readily calculable but they may be computed for the third stage of steady flow from the dimensions of the system by methods in use in hydraulics. The transient stages of flow are usually of relatively short duration and the inability to calculate the flow rate during those stages, does not introduce serious errors in the calculation of average flow rates in gating systems.

The two laws governing the flow of fluids in enclosed channels are (i) Law of Continuity and (ii) Bernoulli's Theorem.

B. Law of Continuity

This law states that under steady-flow conditions the product of cross-sectional area and average velocity at all points in a full channel is the same. Hence, if the cross-sectional areas at points 1, 2, etc., are A_1, A_2, etc. and the velocities of flow at these points are V_1, V_2, etc., V, the volume of fluid flowing per second is given by:

$$V = A_1 V_1 = A_2 V_2 = \text{Constant}$$

It must be emphasized that this law does not necessarily apply to open channels or to enclosed channels which are incompletely full. It applies only when flow is steady, whereas the law applies to both steady and unsteady flow in filled channels.

C. Bernoulli's Theorem

A fluid in motion possesses both potential and kinetic energy.

The potential energy of a fluid is of two kinds:[42] (i) energy of position and (ii) pressure energy. The energy of position of the fluid is the energy due to gravity and is equal to mgh for a mass m of fluid, at a height h above some arbitrary datum plane. This is often referred to as a position head (h) or static pressure head. The pressure energy is the work which the pressure p of the fluid is capable of doing. For unit weight the pressure energy is p/w, w being the specific weight of the fluid. The quantity p/w is known as the pressure head.

The kinetic energy possessed by the fluid is by virtue of its velocity, and is equal to $mv^2/2$ where m is the mass of fluid and v its velocity. The kinetic energy of unit weight is therefore, $v^2/2g$ and is often referred to as the velocity head ($v^2/2g$).

These different forms of energies are related by Bernoulli's Theorem. The theorem states that the total head (sum of pressure, position and velocity head) at any point in a stream flowing without friction is the same at any point in its path of flow. Therefore, for any two points 1 and 2 in the path of flow:

$$\frac{v_1^2}{2g} + \frac{p_1}{w} + h_1 = \frac{v_2^2}{2g} + \frac{p_2}{w} + h_2 = \text{constant}$$

In practice, some energy is invariably lost in friction due to resistance to flow in channels so that if point 1 is upstream as compared to point 2, the total head at the point 2 is less than that at point 1 by an amount equal to the head lost in friction (also, heat loss in case of molten metal flowing through sand molds). If this quantity is h_ℓ, the modified Bernoulli's theorem can be written as:

$$\frac{v_1^2}{2g} + \frac{p_1}{w} + h_1 = \frac{v_2^2}{2g} + \frac{p_2}{w} + h_2 + h_\ell$$

"Another important equation (theoretical) of steady state flow is that based on Torricelli's theorem. This theorem states that the theoretical velocity of discharge through an orifice due to a head "h" over the center of gravity of the orifice is represented in the equation:

$$V = \sqrt{2gh} \quad \text{feet per second}$$ "[45]

This is now recognized as a special case of Bernoulli's Theorem.

Thus knowing the geometry of the system of channels through which the liquid must flow, the rate and velocity of flow at any point in the path can be calculated using law of continuity and Bernoulli's Theorem.

D. Hydraulic Losses in Fluid Flow

When a real liquid is flowing through any system of pipes or ducts, energy losses are produced by the frictional resistance to flow offered by the pipe walls. Losses also occur due to abrupt changes in direction of flow and at points where the pipe diameter changes suddenly, e.g. at orifices and pipe entrances, bends and junctions. The phenomena which takes place at these locations is considered in detail in the following few pages.

(a) Pipe-wall friction:

The factors that contribute towards this type of frictional loss are the roughness of the wall, the nature of the flow (whether laminar or turbulent), the velocity of flow, and the diameter of the pipe. Wall frictional loss also includes the energy dissipated by internal friction in the interior of the stream. Because of the increased internal flow that occurs with the turbulent flow, the frictional losses are greater with this kind of flow than with the laminar flow.

(b) Orifices and Pipe-entrances:

When a liquid flows out of a tank or reservoir (Fig. 2a) through an orifice the liquid inside the tank flows radially towards the hole, as illustrated in fig. 2(b). The particles of the liquid approaching the hole at an angle to the direction of the axis of the jet, are deflected towards the hole by contact with other particles, which results in internal friction and causes a small reduction in the velocity of the outflowing liquid. Another consequence of the change in direction of the motion of particles of liquid is that the particles of liquid cannot immediately turn from the radial direction into the direction of the axis of the jet (Fig. 2b). This causes a contraction in the cross-sectional area of the jet, with the cross-sectional area at the narrowest part only about two-thirds of the hole. This contracted part of the jet is called vena contracta. Contraction does not constitute a hydraulic loss, but results in a diminution of the volume of liquid passing through the hole.

When a liquid is flowing from a reservoir into a pipe, contraction occurs but the stream subsequently expands and fills the pipe (Fig.2c). This causes turbulence which results in internal friction and hence the loss of energy. The"dead region" contains either air or dead liquid, eddies in which also causes energy losses. Since the velocity of the liquid temporarily increases as it passes through the vena contracta, a low pressure exists in the dead region. When the velocities are high,

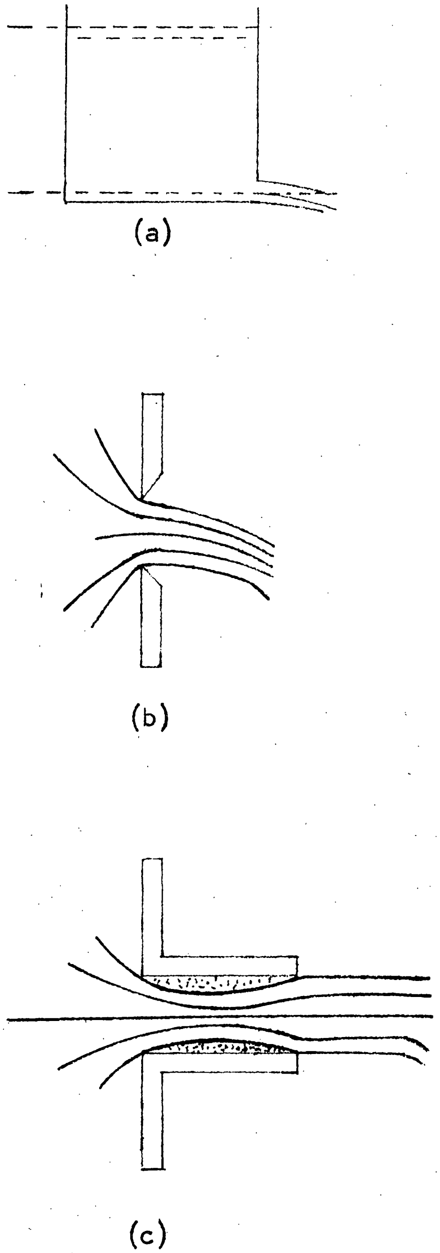


Fig. 2

Diagram Illustrating Discharge from Orifices it is possible for the pressure in the dead region to be less than atmospheric.

(c) Contractions and Enlargements:

Energy losses also take place where an abrupt change in diameter of the duct takes place and at junctions between pipes of different diameters. Fig. 3(a) illustrates the effects produced at sudden contractions which are similar to those occurring at a pipe entrance. Here, the jet contracts and the subsequent expansion of the stream results in turbulence and gives rise to energy losses. Fig. 3(b) illustrates the effects produced at sudden enlargements. A considerable energy loss results due to (1) turbulence produced during the expansion of the stream, and (2) eddies and turbulence produced in the dead regions.

These losses are greater than that produced by corresponding contractions. It may be noted that losses in both contraction and enlargements are produced due to abruptness of the change of section, and may be reduced to a considerable extent by gradual change in section.

(d) Bends and Junctions:

In the case of sharp bends in a piping system, the velocity of the liquid in the direction X (fig. 3c) is abruptly reduced to zero. This may be regarded as causing a sharp rise in pressure. This additional pressure is then expanded in giving the liquid a velocity in the direction Y. The velocity in the direction Y would be entirely from the excess pressure generated by stopping motion in direction X,

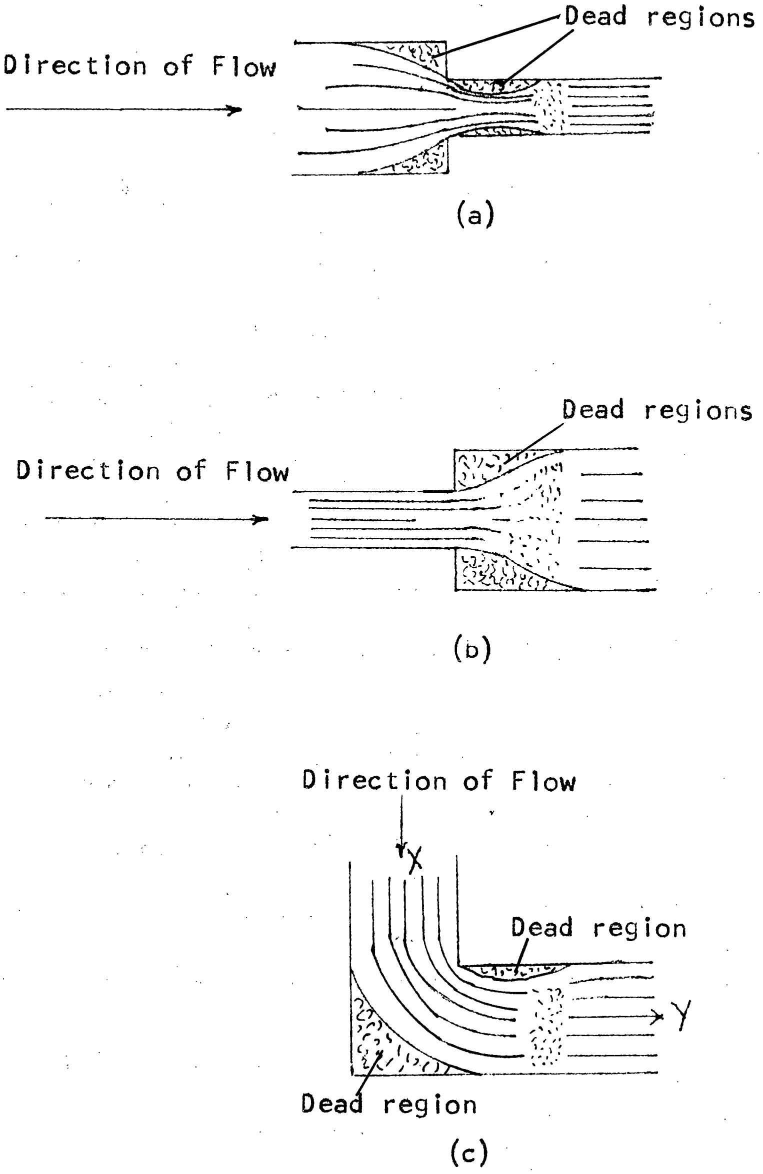


Fig. 3

Diagram Illustrating Flow at:

(a) a sudden contraction
(b) a sudden enlargement
(c) a sharp bend

provided no losses occur in the bend. But in practice, part of the excess pressure is expanded in producing eddies and turbulence in the stream in the dead regions as shown in fig. 2(c). Therefore, the velocity in direction Y is in part generated at the expense of normal pressure, i.e. there is a drop in pressure in passing round the bend. By radiusing the bend, the extent of the dead regions, and hence the energy losses, may be greatly reduced. Pressures less than atmospheric may exist in the dead regions, due to liquid separating from the pipe walls.

Similar behavior occurs at junctions such as "tees". Here the proportion of liquid being diverted around the tee decreases, which increases the loss. The disturbance introduced by the diversion of some of the liquid into the tee also causes some loss of energy in the part of the stream which flows past the tee.

E. Application to Gating Systems:

Application of the above discussed hydrodynamical theory as it effects the gating system shows that when metal is poured into a gating system, at first a transient stage (or stages) of unsteady flow occurs (the system fills and builds up pressure within it). Because of the violent agitation which takes place in this stage of short duration, severe oxidation of the metal may take place, which may lead to the formation of dross which eventually finds its way into the casting. This indicates that the metal first-poured is inevitably damaged, and should not be allowed to enter the mold cavity as suggested by Eastwood[11] and others.

Steady flow is established at the end of the transient stage of unsteady flow. The description given above of the phenomena occurring at pipe entrance, bends, and other changes of direction and section, indicates that even during the steady state flow the metal may be damaged if severe agitation and eddying occur at such locations in the gating system (like sprue entrance, sprue base, gate entrance and exit, etc.). Since such effects become more prominent as the velocity of flow increases, it seems desirable to have low velocity of flow in gating systems. As stated, pressures below atmospheric may exist in the dead regions near bends, enlargements, etc. This is important from the point of view of gating systems, because the walls of the ducts forming gating systems of sand castings are permeable, there is a possibility that the metal stream may entrain mold gases at dead regions. This is another reason for keeping velocities of flow low.

If the gating system is running full during the period of steady flow, knowing the geometry of the system and loss coefficients, the velocities and rates of flow, and hence the pouring time may be computed. This has been explained in detail by Ruddle[42] (Appendix II, p. 156).

As discussed, many gating systems remain partially full of metal. Ruddle discusses the method of calculating the rate of flow in such cases.

In bottom-gating systems, the metal rising in the mold cavity exerts an increasing back pressure on the metal flowing through the gating system, thus reducing the rate of flow. Ruddle[42] shows how to compute flow rate and velocities by the method used for top-gating systems, with due allowance for increasing back-pressure.

When the gate enters the mold cavity in between the top and bottom the flow rate can be calculated in two steps, the first one as for top-gated casting and second as for a bottom gated casting.

In multiple-gating systems the rates of flow from the different gates will in general, vary widely. Here again the general method described above may be used to estimate the rates and velocities of flow from different gates. Methods for making these calculations are described by Ruddle[42].

CHAPTER IV

DISCUSSION ON METAL FLOW VARIABLES

The pertinent variables in a metal flow investigation may be grouped into three arbitrary classifications: metallurgical variables, test pattern variables, and molding variables. A detailed listing and discussion of these variables follows. It is necessary that carefully standardized test conditions be established within the foundry and reproduced from test to test to control these variables and eliminate their effect on metal flow velocity.

I. METALLURGICAL VARIABLES

The known metallurgical variables in a metal flow study are as follows:

Metal composition
Degrees superheat
Surface films
Suspended inclusions
Gas content
Viscosity
Surface Tension
Inclusions precipitating during freezing

A. Metal Composition:

Pure metals, eutectic compositions of alloys, alloys having narrow solidification ranges, and alloys having wide solidification ranges may be listed in decreasing order of fluidity ("the property which allows liquid metal to flow freely and evenly into a mold and fill it before such freezing occurs as would offer an obstruction to further flow"[6]). This may be reasoned out as follows: Pure metals freeze at a constant temperature and therefore have a solidification interval of very short time duration dependent upon the latent heat of fusion for the particular type metal. Practically, the total time for transformation from liquid to solid state involves the volume of metal and rate of heat transfer. However, the important consideration here, is the manner of freezing. The freezing of a stream of metal within a flow channel starts at the outside surface of the stream contacting the mold wall. This process is a gradual inward growth of a relatively smooth solid-liquid metal interface which offers little resistance to flow of the still-liquid interior.

Eutectic compositions of alloys freeze in a similar manner as the pure metals, in that the liquid alloy freezes isothermally or synonymously at a constant temperature. Here, there is no clearly defined surface of demarcation between solid and liquid as when pure metals freeze. The solid progresses in a wave-like manner toward the higher energy-order liquid thus offering more frictional resistance to fluid flow than the characteristically smooth solid-liquid interface of the pure metal.

An alloy having a solidification range is characterized by the first solid particle forming at some temperature and solidification being achieved at some lower temperature. The freezing of a stream of such an alloy within a flow channel again initiates at the surface of the stream contacting the mold wall. A thin layer of fine-grained metal is first formed. Grain growth is restrained due to initial rapid heat transfer from metal to mold material. This diminishes the thermal gradient and solidification progresses inwardly by solid metal fingers called columnar dendrites, preferentially oriented perpendicular to the mold wall. This stage in the freezing process has been called the mushy stage and identifies a network of solid dendrites surrounded by liquid metal near its freezing point. The irregularities of the solidifying network offers physical and frictional obstruction to fluid flow of the still-liquid interior.

With alloys having wider solidification ranges, the physical and frictional obstruction to fluid flow is more pronounced.

B. Degrees Superheat:

The number of degrees temperature above the liquidus temperature is called the degrees superheat. The temperature above which a liquid metal or alloy remains always in the liquid state is called the liquidus temperature.

Pouring temperature has an important effect on the properties of metal casting. Therefore, the metal must be poured at correct degree of superheat to avoid misruns, cold-shuts, gas and shrinkage porosity in castings, etc. Besides this, it is reasonable to expect that metal which is heated to a higher temperature above liquidus will have a longer period as a liquid in the mold, hence it will flow farther than metal not so highly heated.

Thus, the actual determination of the temperature of the liquid metal as it enters the pouring basin is important. The control of temperature is treated more fully in section V of this thesis.

C. Surface Films:

"Some oxide films such as iron oxide on molten steel will "wet" molding sand, enhancing capillary action and increasing fluidity values; on the other hand, the tough aluminum oxide Al_2O_3, is very rapidly formed by contact of the liquid aluminum melt with the foundry atmosphere. This oxide possesses a surface tension value greater than the pure aluminum or aluminum alloy. The high surface tension opposes capillary action and retards flow in a small channel. The melting point of the oxide is near 4000°F. which is considerably higher than that of the parent aluminum alloy, and the oxide will therefore not dissolve in the molten stream"[2].

Since the formation of oxide coating is a function of exposure to the atmosphere, it may be controlled by skimming the liquid alloy in the ladle just prior to actual pouring and then proceeding with a fast pouring rate. A bottom pour ladle may also be used but was not used in this experiment.

D. Suspended Inclusions:

"Suspended inclusions are known to increase the resistance to flow of a fluid when these inclusions are present in sufficient quantity"[47].

Due to the turbulence in flow through the gating system the aluminum oxide film may become broken, become entrapped, obstruct the flow in the flow channel and result in premature solidification.

The effect of this variable is qualitative and one should strive toward eliminating its influence. The means that can be used to minimize its effect are: using a clean ladle, skimming the liquid alloy in the ladle just prior to pouring, a fast pouring rate, and proper gating design.

E. Viscosity:

Whenever a fluid flows or its form changes, forces are brought into action within the fluid which offer resistance to the force causing flow or alteration of form[45]. This fluid properly is known as viscosity. Viscosity may be considered to be internal friction of a fluid during liquid flow[5].

Experimental evidence shows that the absolute viscosity of almost all liquids decreases with a rise in temperature. The changes in temperature which might occur in a liquid metal during its casting, probably would not influence the liquid viscosity to any appreciable extent. Changes in pressure have little if any, effect on the viscosity of most fluids[36].

An extensive study of the viscosity of the molten aluminum-silicon alloys has revealed that the viscosity is at a minimum at the eutectic composition and at a maximum for the alloys having a low concentration of one of the components[49].

F. Surface Tension:

Since the molecular forces on the surfaces of a body of liquid are unbalanced, the free surface of liquid behaves as if it were in a state of stress. Hence, forces act across the surface which are the direct result of molecular attraction. These forces tend toward restricting the flow of a molten stream into a small channel. This effect is more marked in liquid aluminum alloy which does not wet the sand. "The forces across and perpendicular to a line 1 cm. in length in the surface of a liquid in contact only with its own vapor, is defined as the surface tension of the liquid"[45].

The surface tension has very little effect so far as mold filling capacity is concerned since the magnitude of its potential effect can be calculated to be quite small in ordinary size flow channel.

"A high value of surface tension has the effect of increasing the pressure required to cause the metal to enter and flow along a narrow channel, but the direct effect of the true surface tension of many metals is almost overshadowed by the effect of surface films which exert an influence equivalent to that of greatly increased surface tension"[6].

G. Inclusions Precipitating during Freezing:

Certain alloys precipitate a solid inclusion during the freezing process, e.g. hypereutectic iron-carbon alloys, on cooling through the solidification range down to about 2100°F. These alloys precipitate exceedingly coarse graphite flakes. These flakes are called "kish" and float to the top of the liquid melt[44]. These particles thus serve as nuclei for solid metal grains and also become a physical obstruction to fluid flow through a small channel. This variable is not pertinent when using binary aluminum-silicon alloys because no similar inclusions precipitate during the freezing process.

H. Gas Content:

Most metals will dissolve gases from atmosphere if time permits. The solubility of gas varies as the square root of gas pressure above and around the metal[17]. The solubility of gas is considerably higher in liquid metal than in solid metal[17,50]. Therefore, the atomically dissolved gas tends to evolve molecularly leaving behind gas holes, the number of which varies with freezing time.

When pouring aluminum, oxygen, hydrogen and water vapour which dissociates forming hydrogen and hydroxyl ions are the main considerations. The oxygen reacts with the liquid aluminum alloy forming the tough aluminum oxide, with little or no oxygen gas absorbed into the metal underneath. When pouring aluminum, hydrogen is the gas of major importance, as it is readily absorbed into the liquid melt[17].

Metal flowing in a channel is often separated from the mold wall by a thin layer of gas, thus slowing down the rate of heat transfer, increasing solidification time, and allowing the metal to flow farther.

Gas issuing from a moving stream may break up oxide films or prevent the formation of them, thus improving fluidity. Looking from a different view point, gases that are given off the metal may prevent metal from flowing into a channel unless the mold material is sufficiently permeable to allow the gas to escape. Proper molding technique and/or gating system design will eliminate the possibility of this back pressure. A suggested method for control of this variable is discussed in section V of this thesis.

II. TEST PATTERN VARIABLES

A number of test patterns are proposed by various investigators for metal flow investigations of gating systems. The horizontal gating system has received far more attention from research workers than any other kind. The major control of the test pattern variables lies in the design of the test pattern. The test pattern should be designed so as to facilitate ease of handling.

Once the test pattern is made the following variables, with the exceptions of pouring rate, pressure head, and pouring height are fixed:

Pressure Head
Energy losses due to turbulence in flow
Cross-sectional area of flow channel
Cross-sectional shape of the flow channel
Pouring basin design
Pouring rate
Pouring height

A. Pressure Head:

"The pressure head is considered the effective height of liquid metal above the entrance to the flow channel acting to force the metal through the ingate"[1].

Since it is difficult to apply pressure head instantaneously, investigators have centered their efforts on standardizing the application of pressure head. Various means have been suggested to maintain the pressure head constant. Specially designed pouring basin[1] has been used for this purpose. Another method uses a fusible plug at the top of the sprue, which burns out upon complete filling of the pouring basin.

In any case, the gating system should be designed so that constant pressure head is maintained on the liquid metal during the filling of the mold. The gating system should also be designed to give minimum of turbulence.

The pressurized gating system design allows the sprue to be filled with molten metal more rapidly than it can run out into the flow channel. A fast pouring rate in a pressurized gating system eliminates vortex effect at the down sprue entrance and consequent air aspiration into the mold cavity.

The method used in this investigation to keep the pressure head constant, is discussed in chapter V of this thesis.

B. Energy Losses due to Turbulence:

"Liquid metals can flow either in streamlined, laminar manner or with turbulence of varying amounts. In laminar flow, the particles follow well defined, non-intersecting paths without turbulence. In turbulent flow, however, the paths of the liquid particles cross and recross one another in an intricate pattern of interlacing lines with eddies. The degree of turbulence can vary widely from slight to violent, depending on conditions of flow"[16].

Sharp changes in the cross-sectional area of the flow channel and in the direction of flow greatly affects the degree of turbulence in a flowing stream of metal. Severe turbulence from such changes are undesirable because of severe metal oxidation, fracture of surface oxide films, and also because air and mold gases are thereby aspirated into the system.

Ways of reducing turbulence in the gating system are discussed in Chapter 3 of this thesis.

C. Cross-sectional Areas and Shape of Flow Channels:

"The effect of channel size on length of flow of a molten metal is readily apparent; small cross-sections result in shorter flow. This is so because solidification is more rapid in smaller cross-sections and probably also because the effect of certain resistance to flow (such as surface tension, surface films, and others) becomes of more relative importance in smaller channels."

Cross-sectional shape makes little diffreence except for the ease with which the pattern is molded. Because of the ease with which the pattern may be drawn from the sand, a trupezoidal section is believed to be the most practical.

D. Pouring Basin Design, Pouring Rate and Pouring Height:

Increasing the height of pouring increases the kinetic energy of the liquid metal going into the gating system causing turbulence of flow, splattering and erosion of mold may result in cold shuts, oxide inclusions and sand inclusions.

The pouring height, that is the distance from the pouring lip to pouring basin should be short and consistent from test to test. "By providing a pouring basin, the kinetic energy of the metal being poured is largely dissipated before it enters the sprue. The basin should be large enough to permit easy control of the pouring stream without undue splashing and of sufficient depth to prevent the formation of a vortex in the sprue"[30]. The pressurized gating system and the use of overflow well to insure a constant pressure head on the liquid metal going into the system will further control this variable.

Pouring rate is a significant factor, and should be controlled to obtain consistent results in metal flow investigations. It is easier and convenient to control the pouring rate with a stop watch. Thus, the use of a stop watch in foundry practice is recommended to determine pouring time and to insure that the proper times are maintained. The pressurized system (after initial stages of pouring) will also control the pouring time.

It is recommended to use a fusible plug at the top of the down sprue which burns out after the pouring basin has been completely filled, to compensate for these variables.

III. MOLD MATERIAL VARIABLES

Molding materials that can be used are, green molding sands, dry molding sands, metals, graphite, investments, and others. Within each group numerous variations are possible. For example, one can have high alloy steel, plain carbon steel, aluminum alloys, etc., in the metal classification. Similarly, one can vary the amount of additives, moisture content, binder content, for green molding sands. The possible combinations of variables are practically infinite.

The influence of the molding material on metal flow depends on the type selected for investigation. Assuming other variables equivalent, a green sand mold material has a lower thermal conductivity than a metal mold material, solidification thereby takes place more slowly, and reduces the resistance to metal flow.

To eliminate the errors attributed to mold material variables in the investigation, one needs only to standardize the molding ingredients and method of molding, then control these from test to test. The effect of one mold material factor can be investigated by varying it, and keeping others controlled.

The molding materials and parameters of molding method peculiar to the CO_2 process which may be varied are:

Amount and type of binder
Amount and type of Additives
Mulling cycle time and method
CO_2 gassing time and method of application
CO_2 gas pressure
Temperature of CO_2 gas
Mold curing time

CHAPTER V

THE INVESTIGATION

I. STATISTICAL DESIGN OF EXPERIMENT

A. Introduction

Statistics plays an important role in designing an experiment efficiently so that a maximum amount of information relevant to the problem under investigation is obtained with a considerable saving in time, money, personnel, and experimental material. It also plays an important part in analyzing and interpreting the results of the investigation.

The design of an experiment means planning an experiment so that information relevant to the problem under investigation will be collected with the desired degree of accuracy at minimum cost and time. Choice of design in any particular situation depends upon the kind and variety of data to be obtained, the nature of material with which we are working, time, effort, and money available, and degree of precision required.

It is a common characteristic of research experiments that, when they are repeated, the effects of experimental treatments vary from trial to trial. This variation introduces a degree of uncertainty into any conclusions that are drawn from the results. Statistics deals with the interpretation of data so that these uncertain conclusions are accompanied by probability statements expressing the degree of confidence which the researcher has in such inferences. In order to attach a probability statement to estimated differences, Ostle[35] has stated that replication, randomization, and local control are required conditions for an experimental design.

The failure to produce identical results is termed the experimental error. It is not possible to get rid of this experimental error completely, so in designing the experiment we try to introduce as many controls as are feasible to make this error as small as possible. But the design of experiments also makes it possible to get an estimate of the size of the experimental error that remains after those controls have been introduced.

B. Importance of Replications

Replication means repetition of the basic experiment. Since variability is almost unavoidable, the replication of given conditions should be practiced in nearly all experimental work to show reproducibility of results obtained in the experiment. Replication is desirable because it provides a more accurate estimate of experimental error which acts as a "basic unit of measurement" for assessing the significance of observed differences between treatment effects. Replications should be set to control as much of the variation as possible, resulting in the smallest experimental error. The number of replications for an experiment depends on the degree of precision desired, scope of the experimental work, amount of variability present in the experimental material, available resources, including personnel and equipment.

C. Randomization

Perhaps the most frequently invoked assumption is that the observations (or the errors there in) are independently distributed. Randomization makes the test valid by making it appropriate to analyze the data as though the assumption of independent errors is true.

Randomization does not mean just to manipulate things into some order that looks haphazard. An important feature of randomization is that it should be an objective impersonal procedure. Another important feature of randomization is that it eliminates personal biases of the people taking part in the experiment including the experimenter himself. A substantial amount of uncontrolled variation may arise from the subjective effects due to these biases.

From the above discussion, it is clear that the effect of randomization is to transform the unknown variations of the experiment material into independent and random variations to obtain unbiased estimates (this is accomplished through assigning numbers to specimens from published tables of random numbers) of the effects of the treatments and also the reproducibility of these effects.

Sometimes complete randomization is either impossible or uneconomical. In such cases one should not insist on complete randomization, neither should he agree to the use of a completely systematic design, since some degree of randomization is required for the valid application of statistical analyses. Clearly, some intermediate position between the two extremes of complete randomization or a strictly systematic design is often most realistic.

D. Local Control

It was discussed above that replication and randomization make a valid test of significance possible. Local control refers to the amount of balancing, blocking and grouping of the experimental units that is employed in the adopted statistical design. The function of the local control is to make the experimental design more efficient, that is, it makes the test of significance more sensitive by reducing the magnitude of the estimate of experimental error.

Grouping means the placing of a set of homogeneous experimental units into groups in order that different treatments may be applied to different groups.

Blocking refers to the allocation of the experimental units to blocks in such a manner that the units within a block are relatively homogeneous. Thus, the knowledge concerning the nature of the experimental units helps in designing the experiment in such a way that much of the part of the anticipated variation will not be a part of the experimental error.

Balancing means the obtaining of the experimental units, the grouping, the blocking, and assignment of the treatments to the experimental units in such a way that a balanced configuration results. It may be noted that we can have little or no balance, partial, approximate or complete balance in any particular design.

E. Split-Split-plot Design

For the purpose of this investigation it was decided to use two (pressurized and unpressurized) gating systems with two gates in each system, three different degrees of superheat, and one metal composition. The number of replications taken was four.

With this background information the author decided to use a split-split-plot type of design. This particular design would give the main effects of pressure, superheat and gates, and the interactions of the pressure with superheat, superheat with gates, gates with pressure and gates with superheat and pressure. The layout of one replication is shown in the figure 4.

The two gating systems (pressurized and unpressurized) were laid out as a whole plot while three degrees of superheat were laid out as split plots within each system. The two systems were randomized by using table of random numbers from Dixon and Massey[8]. The three degrees of superheat were allotted to three randomized molds within each gating system.

II. INSTRUMENTATION PRINCIPLE AND USE

A. Measurement of Time and Indication of Steady State

The author used SR-4 strain gages as sensing elements for measuring time and to get an indication of steady state flow. The application is explained in part F of this chapter.

(a) The Bonded Wire Strain Gage[37]:

The bonded wire resistance strain gage consists of a pattern of very small diameter wire cemented between two pieces of thin paper as shown in figure 5.

The wire used has the property of linear variation of electrical resistance with strain. In order to measure the strain in a machine or

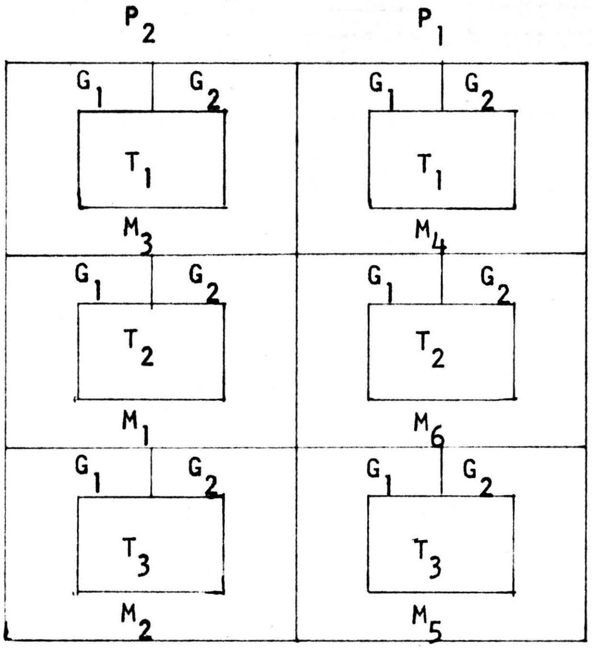


Fig. 4 Layout of One Replication

Legend:

P_1 = Pressurized System

P_2 = Unpressurized System

T_1 = 300°F. Superheat

T_2 = 200°F. Superheat

T_3 = 100°F. Superheat

G_1 = Gate one

G_2 = Gate two

M_1,----M_6 = Mold numbers

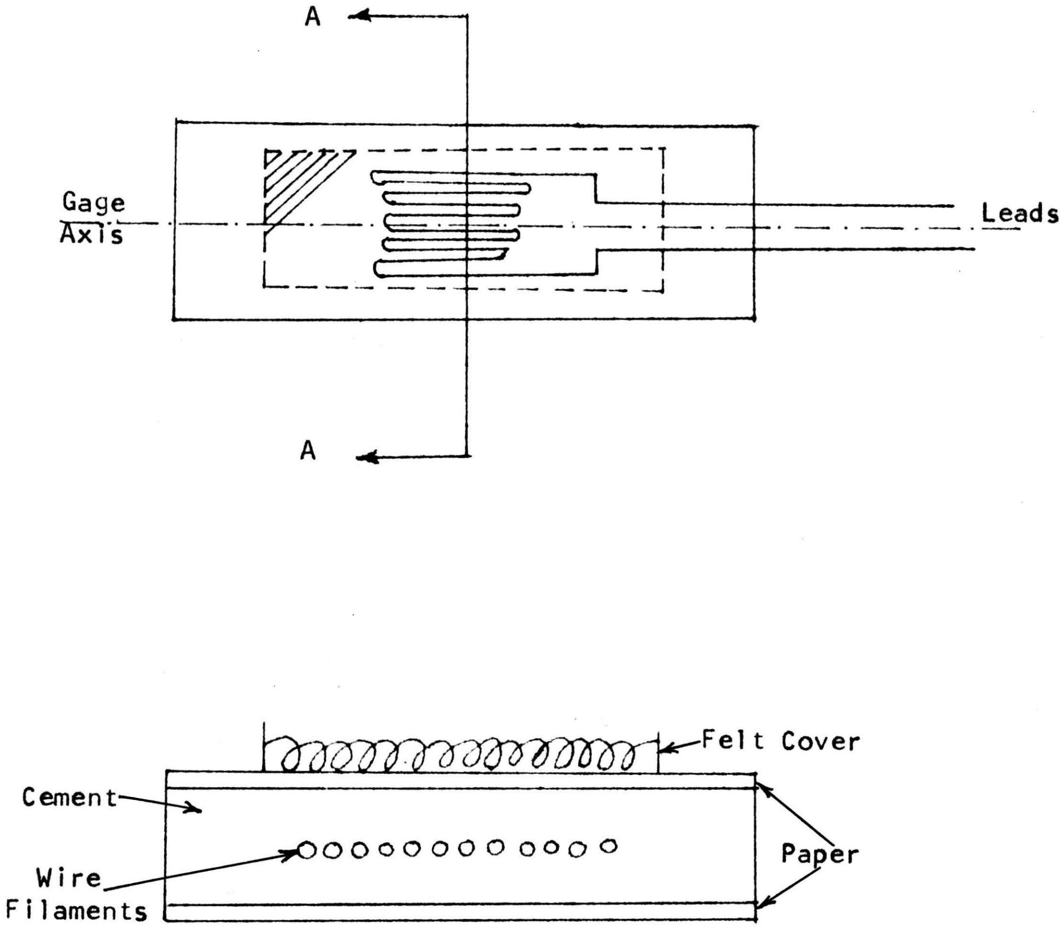


Fig. 5

Different Elements of SR-4 Strain Gage

structural member, one or more of these strain gages are cemented to the surface of the part and allowed to dry. The strain gage is connected to a wheatstone bridge for indicating small changes in resistance. Once this is done, the strain gage will follow and report any strains occurring in the test surface in the direction of the gage axis.

The dimensionless relationship between change in gage resistance and change in length is called the gage factor of the strain gage and expressed mathematically as:

$$F = \frac{\Delta R/R}{\Delta L/L} \qquad (1)$$

where F = Gage factor

R = Initial resistance of the strain gage

L = Initial length of the strain gage

ΔL = Change in length of strain gage

ΔR = Change in resistance of strain gage

The gage factor of a strain gage is a measure of the amount of resistance change for a given strain and thus an index of the strain sensitivity of the strain gage. From equation (1)

$$\frac{\Delta L}{L} = \frac{\Delta R/R}{F}$$

but $\frac{\Delta L}{L}$ = unit strain

$$= \frac{\Delta R/R}{F}$$

Thus unit strain equals the unit change in resistance, $\Delta R/R$, divided by the gage factor. For finding out unit strain, it is necessary to measure ΔR precisely. This can be done with the help of a wheatstone bridge. In figure 6, a circuit for balanced bridge is shown.

As the bridge is balanced, no current flows through the galvanometer and hence the voltage across the galvanometer is zero. Therefore, the voltage at A is equal to voltage at C.

Voltage drop from B to A = voltage drop from B to C

i.e. $I_1 \times R_1 = I_2 \times R_2$

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \qquad (2)$$

Similarly, the voltage drop from A to D must equal the voltage drop from C to D. Furthermore, since no current is flowing across the galvanometer branch, the current through R_1 must be the same as the current through R_4, and the current through R_2 must equal that through R_3.

$$I_1 R_4 = I_2 R_3$$

i.e. $\dfrac{I_1}{I_2} = \dfrac{R_3}{R_4}$

From equations 2 and 3 $\dfrac{R_2}{R_1} = \dfrac{R_3}{R_4}$

i.e. $R_1 = \dfrac{R_2}{R_3} \times R_4$

Thus, when the bridge is balanced, R_1 can be determined by knowing R_4 and the ratio R_2/R_3 with a high degree of precision.

An extension of these principles relating strain-gage application to a cantilever beam, calibrating, and recording can be found in the literature[3,37].

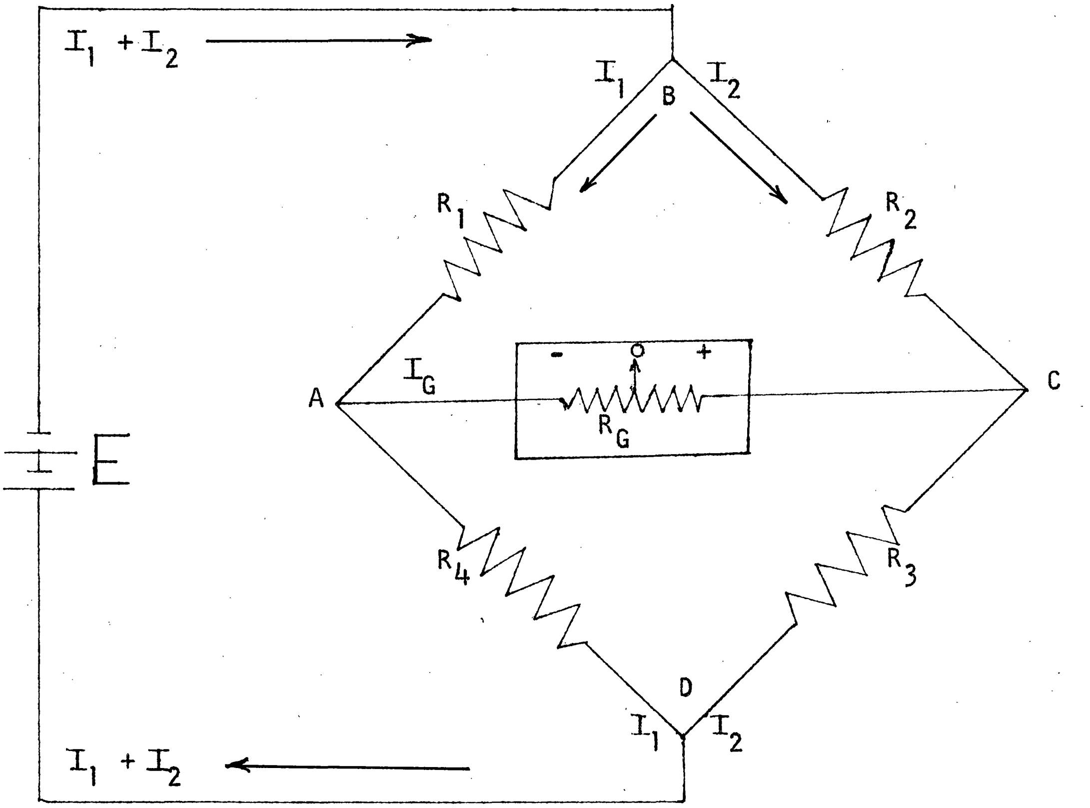


Fig. 6

Wheatstone Bridge Circuit for Balanced Bridge

(b) Measurement System:

The basic system of measurement employed was the conversion of strain applied by the weight of the metal to an electric signal proportional to the strain, amplification of this signal and recording of this signal on a permanent record. This was done by a Sanborn amplifier and recording unit.

The operating procedure was followed as per the instruction manual[22].

Indication of steady state and measurement of time are discussed in part F of this chapter.

B. Temperature Measurement

(a) Thermoelectric Measurements:

A thermocouple is composed of two dissimilar wires joined together so as to produce an electromotive force when the junctions are at different temperatures. If one junction is maintained at the temperature of the melting ice or room temperature, the temperatures of other junctions can be determined by measuring the electromotive force developed by the circuit. The electromotive force developed by the circuit are small, usually a few thousandths of a volt.

(b) Laws of Thermoelectric Circuits:

There are three laws for thermoelectric circuits composed of homogeneous conductors, which should be understood for making efficient use of thermocouples.

(1) "Law of Homogeneous circuit: An electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone.

(2) Law of Intermediate metals: The algebraic sum of the thermal emf's in a circuit composed of any number of dissimilar metals is zero, if all the circuit is at a uniform temperature.

(3) Law of Intermediate temperatures: The thermal emf developed by any thermocouple of homogeneous metals with its junction at any temperature T_1 and T_3 respectively, is the algebraic sum of the emf of the thermocouple with its junctions at temperatures T_1 and T_2 respectively and the emf of the same thermocouple with its junctions at temperatures T_2 and T_3 respectively."[12]

(c) Temperature Recording at Gates:

In this experiment two chromel-alumel thermocouples were used to measure temperature at gate one (near the sprue) and gate two (farther from the sprue). Chromel-alumel 22-gauge wire elements were twisted to form the hot junction. The thermocouple elements were insulated with ceramic and rubber sleeves from hot junction to cold junction. The hot junctions were mounted into the gates so that proper contact between the thermocouple and metal can be maintained. (See photograph 5 and 8, p. 145-6). The cold junctions were at Honeywell recording millivoltmeter and Sanborn low level preamplifier for gate one and gate two respectively. These instruments were used to provide suitable amplification of the emf for recording. The Sanborn low level preamplifier was operated as per instructions in the Sanborn

Manual[22].

(d) Temperature of Metal in Ladle:

The temperature of molten metal in ladle was determined by using a chromel-alumel thermocouple (similar to one used by Agee[2]) connected to a Leeds and Northrup potentiometer. Photograph 12 (Appendix III.) illustrates the instrumentation used in this experiment.

III. EXPERIMENTAL SET-UP

The following paragraphs contain a list of materials and equipments used in the performance of the experimental phase of this investigation.

Pattern: The cope and drag half of the pattern (see figs. 7 and 8) were mounted as a pattern mount.

The cope half consisted of down sprue for pressurized (see fig. 9) and unpressurized (see fig. 10) gating systems, and two ingates (see fog. 7).

The drag half consisted of a runner, with a blind hole previously drilled at about 3/4" from one end and used to position the sprue (see fig. 8).

Photographs 2 and 3 (Appendix III) illustrates the pattern used in this investigation.

Sand: AFS 60 dry, clay-free silica sand was used in making molds.

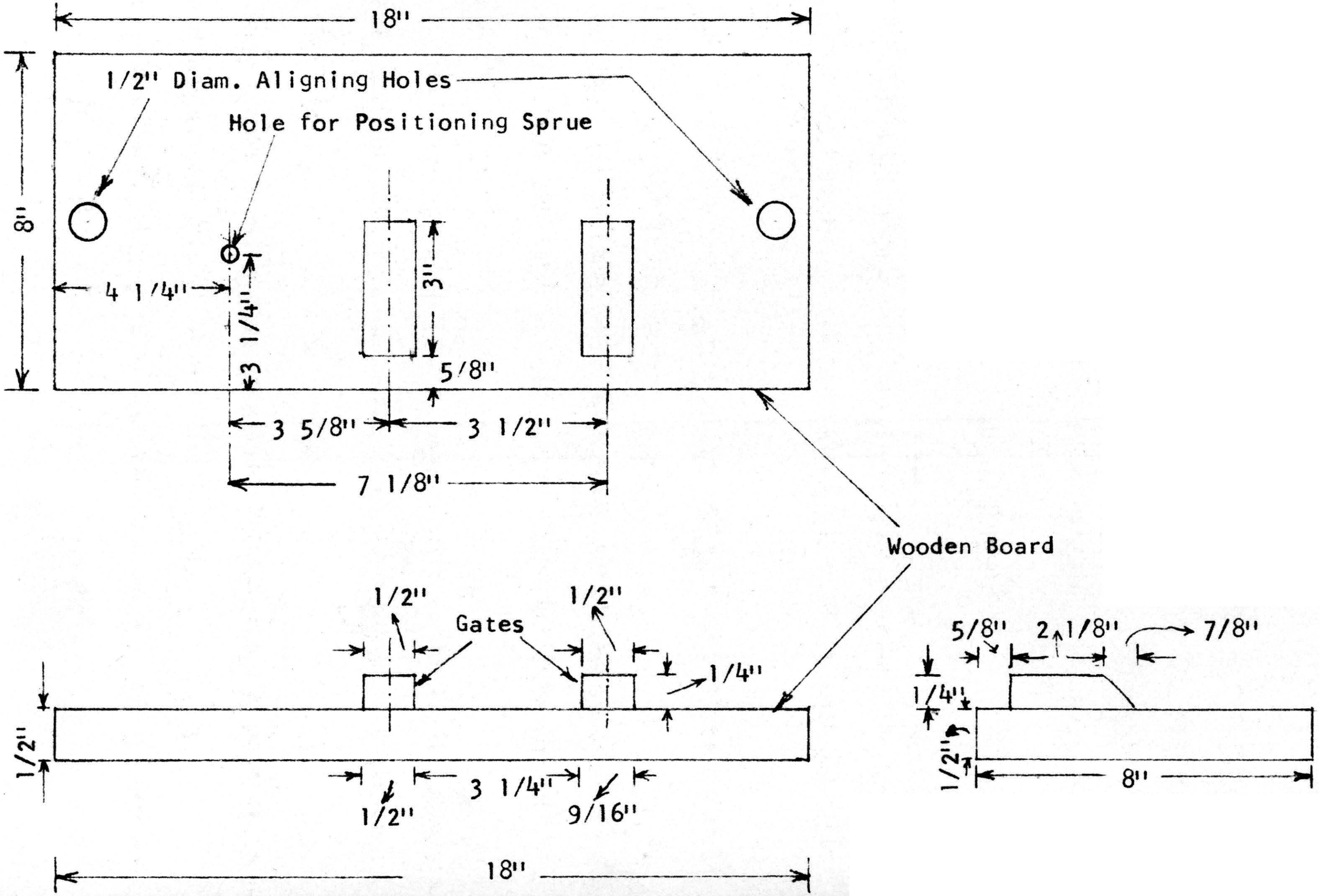


Fig. 7 (not to scale) Cope-Half of the Pattern

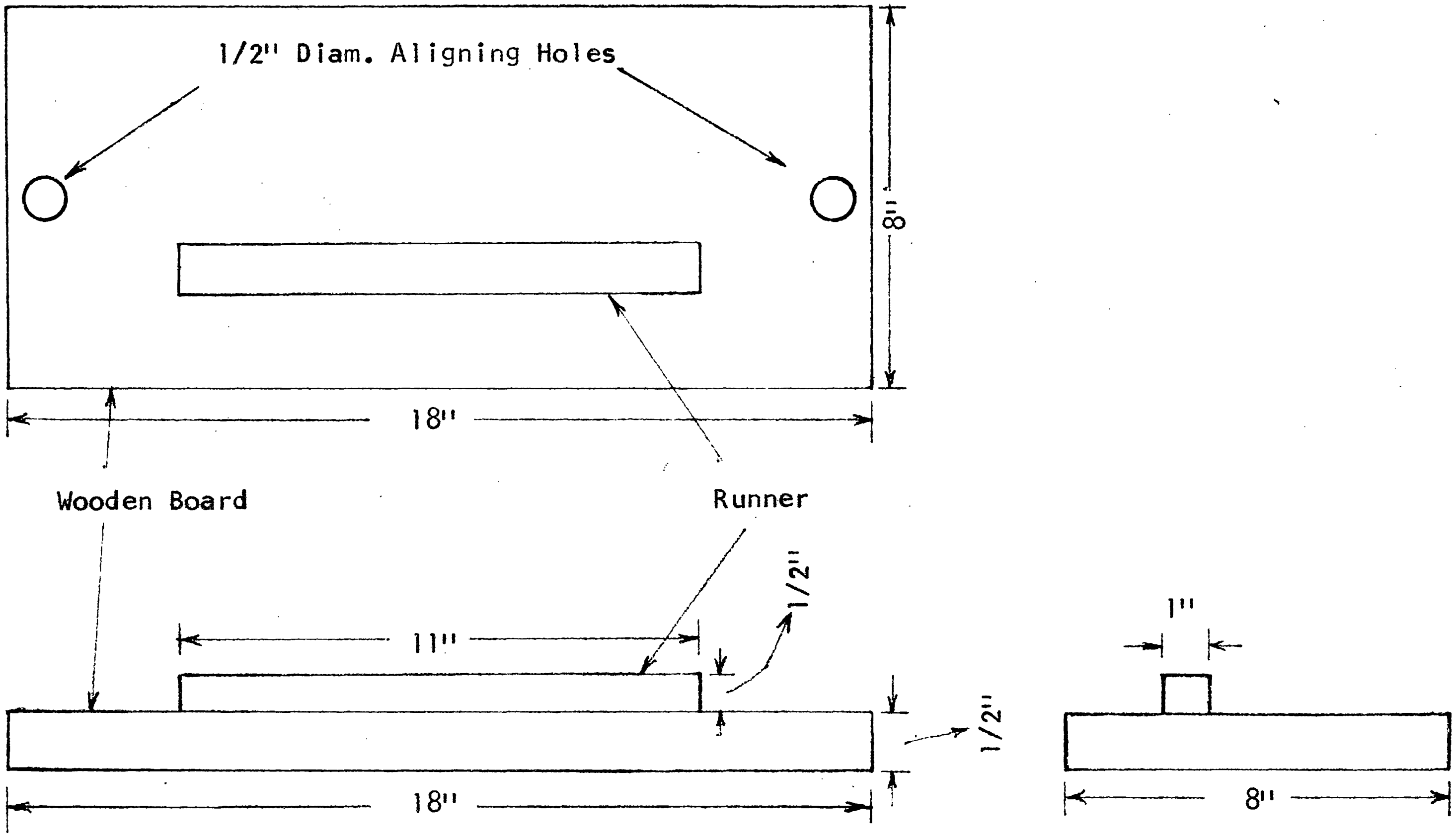


Fig. 8 (not to scale) Drag-Half of the Pattern

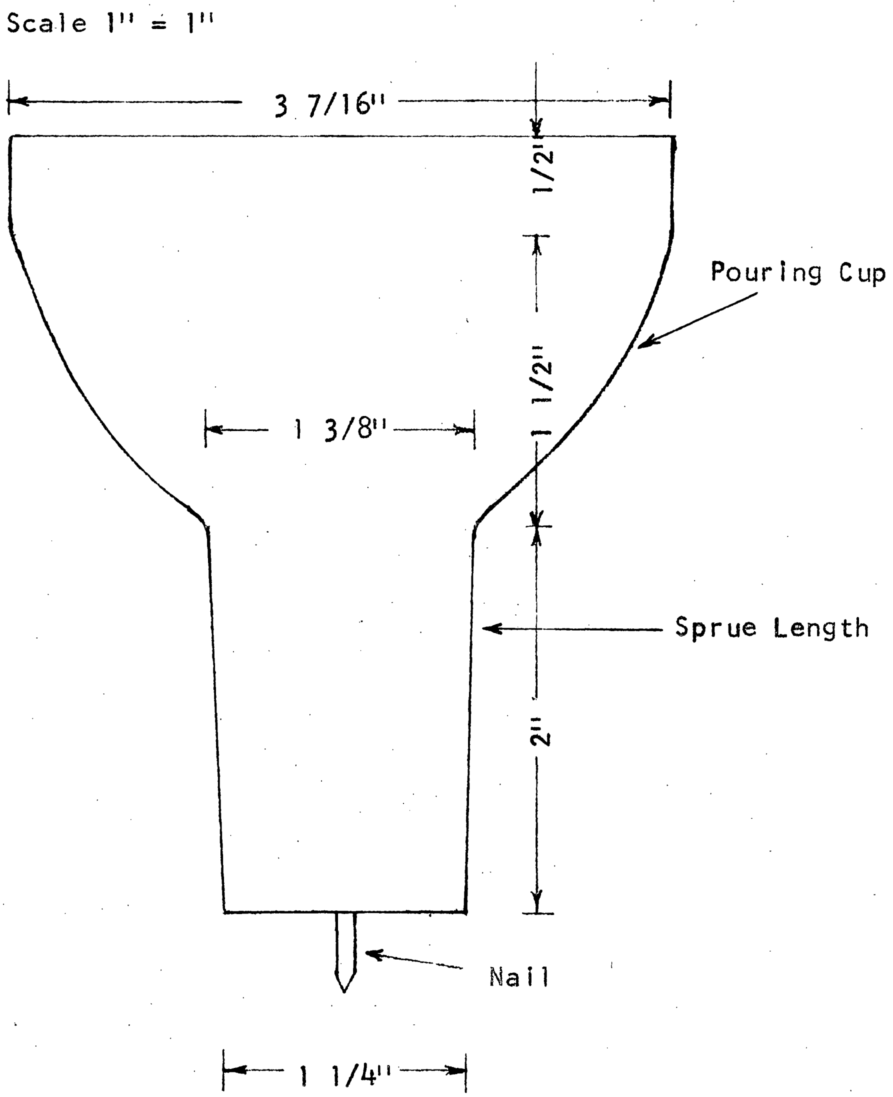


Fig. 9 Sprue for pressurized system.

Scale 1" = 1"

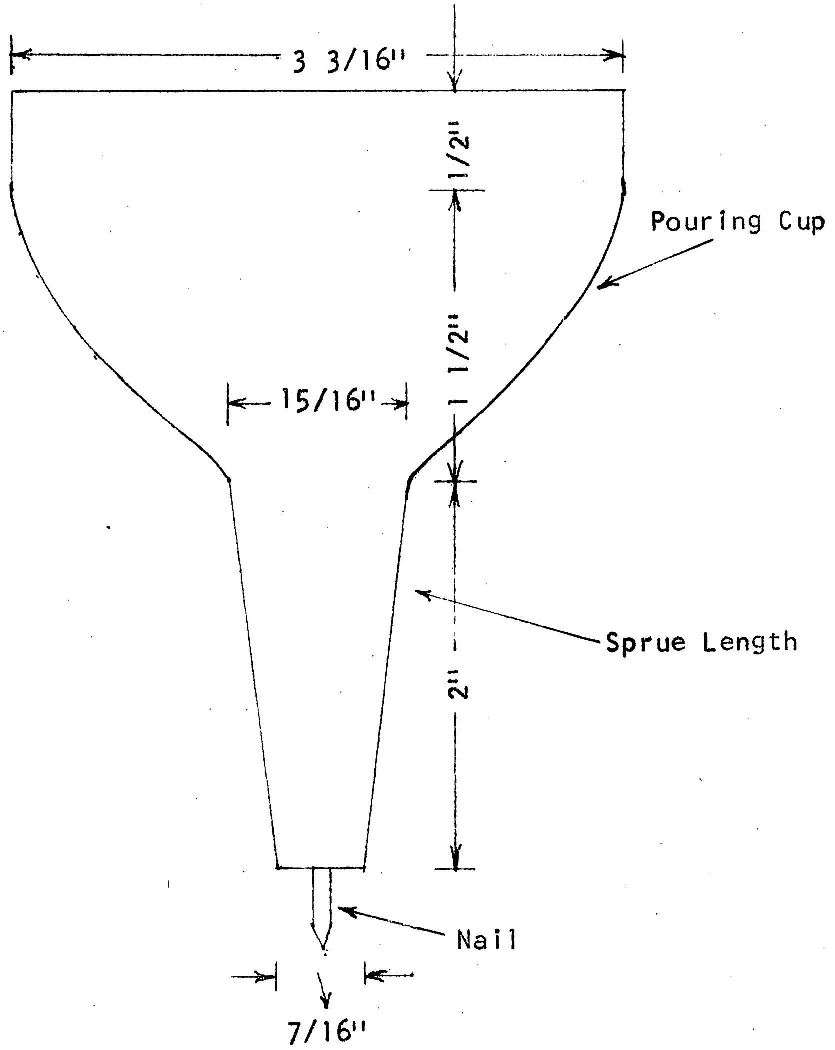


Fig. 10 Sprue for unpressurized system.

Fairbank's Scale: Used to weigh the sand.

Sodium Silicate: Commercial grade liquid organic sodium silicate (4% by weight) was used as a binder.

Portable Scale: Used to weigh sodium silicate.

Muller: Machine used to mix sand and sodium silicate.

Mold Flasks: Used to hold the molding mixture. Pins and lugs were incorporated on flasks to assure proper alignment of the cope and drag half of the mold. Photographs 2 and 3 (Appendix III) illustrates the cope and drag half of flasks used in this investigation.

Parting Sand: Used to prevent mold material from sticking to the pattern.

Levelling Bar: Flat and smooth wooden bar with one edge round and the other sharp, used to remove extra molding material from above the top surface of the flasks and to level the mold surface.

Rammer: A wooden tool with a round head at one end and a wedge-shaped head at the other, used in packing the sand in the flasks, around the pattern in making the molds.

CO_2 Gassing Unit: A portable cylinder with pressure indicator and a rubber cup, used to inject CO_2 gas into the molds. (See Photograph 1, Appendix III).

Revecon Reverberatory Furnace: A melting furnace that can be tilted to pour the molten metal, obtained from International Foundry Supply Co., Rending, Pa., Type 320/500. Photograph 6 (Appendix III), illustrates the furnace used in this investigation.

Aluminum 12-Percent Silicon: Commercial Alcoa ingots.

Flux: A material used to prevent furnace contamination and abet impurity removal.

Degassing Tablet: Solid chloride-base tablet used to remove H_2 from the molten metal.

Ladle: A metal receptacle shank-type, used to transport and pour the molten metal into the CO_2 molds. Fig. 12 and photographs 6, 7, 8, 9 (Appendix III) illustrates the use of ladle in this investigation.

Thermocouples: Three chromel-alumel thermocouples were used to measure temperature of the molten metal in the ladle and temperature of the metal emerging from the two gates. Fig. 12 and photographs 7 and 8 (Appendix III) illustrates the thermocouples used in this investigation.

Millivoltmeter Potentiometer: Precise voltage measuring device, obtained from Leeds and Northrup Company, Philadelphia, Pa. Range -11 mv. to 101 mv. used in measuring the temperature of the molten metal in the ladle (see fig. 12, and photograph 10, Appendix III).

Cantilever Beams: Two cantilever beams (see photograph 4, Appendix III) with strain gages mounted on them were used to support the mold and catch pans (collecting steady state metal). Fig. 12 and photograph 5 (Appendix III) illustrates the cantilever beams used in this investigation.

Strain gages: SR-4 strain gages were used as sensing elements, for measuring time and to give an indication of steady state condition. (Their use is described in part V of this chapter). Photograph 4

(Appendix III) shows strain gages mounted on the cantilever beams. Fig. 12 shows the strain gages connected to Sanborn amplifier.

Sanborn Amplifier with Recording Unit: Sanborn amplifier model 150 with four different channels, obtained from Sanborn Company, Waltham 5, Massachusetts, used for (i) measuring the temperature at gate two (farther from the sprue), (ii) giving an indication of steady state condition, (iii) measuring time of steady state metal flow. Photograph 10 (Appendix III) shows the Sanborn amplifier and fig. 12 illustrates its use.

Honeywell Millivoltmeter: Honeywell millivoltmeter model No. 153X10-PSH-II-III-20, obtained from Minneapolis-Honeywell Regulator Co., Brown Instruments Div., Philadelphia, Pa., Range 0-60 mv. used to measure the temperature at the gate one (near the sprue). Photograph 10 (Appendix III) shows this instrument and fig. 12 illustrates its use.

Waste Metal Pan: Used to catch the initial and final metal during unsteady state condition. Fig. 12 and photograph 7 (Appendix III) illustrates its use.

Catch Pans: Used to catch the steady state metal (going into the final results). They were placed on the cantilever beam B (shown in photograph 4, Appendix III). Figure 12, and photograph 8 (Appendix III) illustrates the use of catch pans. Photograph 9 (Appendix III) shows the catch pans and the solidified metal.

Troyner's Scale: Used to weigh the solidified metal in air and in water.

IV. FIRST PRELIMINARY INVESTIGATION

A brief preliminary investigation was made to test the working of different facilities and instruments mentioned above.

Aluminum - 12% silicon was used. Molds were prepared and metal was melted. The molten metal was poured directly into the sprue. The molding, melting and pouring technique used were the same as in final investigation.

During this investigation, it was found that:

1. It is not possible to fill the metal to the top of the sprue thus, not allowing the system to attain the steady state condition. This was due to large gate exit area.

2. Also, the thermocouple response was not rapid enough for the short pouring cycle.

V. SECOND PRELIMINARY INVESTIGATION

After the first preliminary investigation the following changes were made:

1. New sprues were made, both for pressurized and unpressurized gating system, with the pouring basin incorporated at its top, with dimensions as shown in figure 9 and 10.

2. Gate exit area was cut down to one-half.

3. Instead of thermocouple wires being welded, it was decided to twist the wire ends and then insert into the gates, so that proper

contact between the thermocouple and molten metal is maintained to get the rapid response.

With these changes second preliminary investigation was carried out. The purpose of this investigation was to justify the use of different facilities and equipments used and to effectively standardize the overall procedure.

The eutectic alloy of aluminum -12 percent silicon was poured into four different molds (two for pressurized and two for unpressurized gating systems), prepared under the same standard conditions from a basic mix of 4 percent (by weight) liquid organic sodium silicate binder and AFS 60 dry, clay-free, silica sand.

The aluminum alloy was melted in a Revecon reverberatory furnace using a direct neutral flame. Flux to promote melting, and a chloride-base degassing tablet to remove gases from the molten metal were used. Metal was tapped in a preheated ladle and poured at 1550°F. (475°F. superheat) and 1450°F. (375°F. superheat) into two molds in each system. The object was to equalize the thermal gradient so that the temperature of the metal emerging from the gates would approximate 300°F. and 200°F. respectively by the time the system attained the steady state condition. Briefly a 175°F. temperature drop between ladle temperature at start of pouring and temperature of metal at the gate at time of acquiring steady state in the system was predicted.

The temperature of the metal in the ladle was measured by a chromel-alumel thermocouple connected to a Leeds and Northrup potentiometer, and the temperature of the metal emerging from the gates was measured by two chromel-alumel thermocouples connected to a Sanborn amplifier with recording unit, and a recording Honeywell millivoltmeter.

The speed of the recording paper of the Sanborn recording unit was set at 1/4 ft./min. The starting and stopping of collecting the steady state metal in catch pans was marked on this paper by clicking a switch on the Sanborn unit. The distance between these two marks gave the time of flow.

From the results of this investigation it was found that:

1. Because of the possibility of human error in clicking the switch, a more efficient and accurate time measuring device should be used.

2. It is not possible to obtain exactly, the desired degrees of superheat Viz, 300°F., 200°F., and 100°F. of the metal emerging from either gate.

3. Temperatures of the metal issuing from two gates were different, but the difference was nominal (range 7-22°F., average 14°F.).

After this second preliminary investigation it was decided to use a second cantilever beam with strain gages on it, to support the catch pans and measure the time of metal (steady state) flow more accurately. Because it was not possible to obtain the desired degrees of superheat (300°F., 200°F., and 100°F.) of the metal issuing from the gates, it was decided to pour the metal from the ladle at 1550°F., 1450°F., and 1350°F. in each replica and measure the temperature of the metal issuing from both gates, and to use a statistical design which will adjust the deviation of the observed value from the desired value.

VI. FINAL INVESTIGATION

The final investigation, incorporating the above mentioned change, and suggested method of procedure (see fig. 11) follows as outlined:

A. Ingredients and Preparation of Ingredients
B. Making of Molds
C. Preparation of Molten Metal
D. Pouring of Metal and Recording of Data
E. Velocity Determination

A. Ingredients and Preparation of Ingredients:

(a) Ingredients:

1. Liquid organic sodium silicate (4 percent by weight) was the binder.
2. AFS 60 dry, clay-free silica sand.

(b) Preparation of Ingredients:

Both ingredients were weighed, sand on a Fairbank's scale and sodium silicate on a portable scale. The dry sand was then charged into the muller and mixed for about one minute. Liquid organic sodium silicate was then added, and the mixture mulled for approximately five minutes. The batch was then used to prepare molds before it begins to harden.

B. Making of Molds:

(a) Molding Procedure:

The cope half of the flask was placed on a smooth wooden

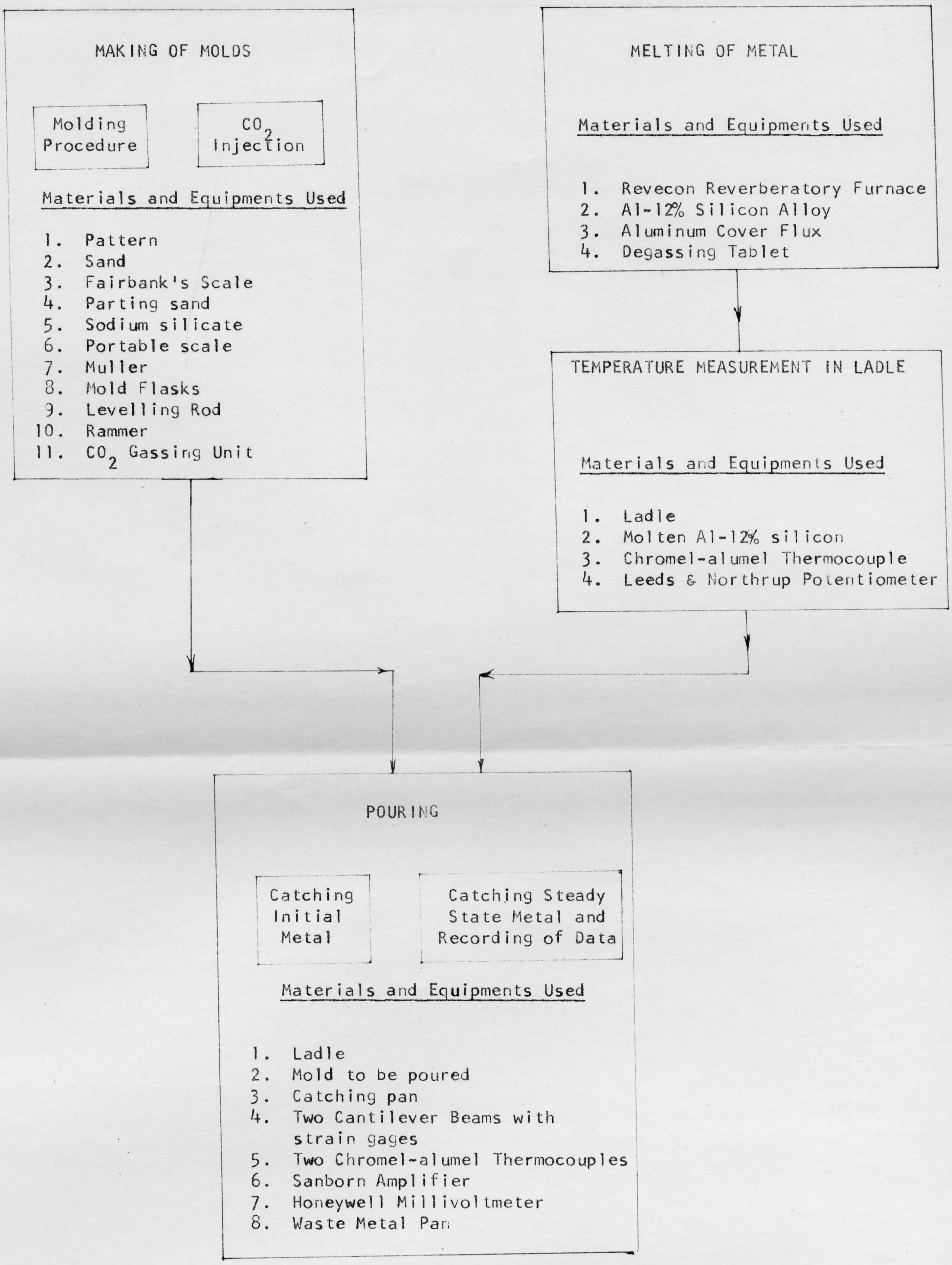


Fig. 11

Flow Diagram Illustrating Experimental Procedure board with the side having grooves for gates up. The pattern was then mounted on the flask with the runner side up. The drag flask was then placed over the pattern, and parting sand was sprayed over it with the help of a cloth bag. Care was taken to see that all the three were aligned.

The mix from the muller was then loaded into the drag flask and hand rammed to the top of the flask. The excess mixture from the top was then removed with a levelling rod. The top was then covered with a smooth wooden board and the system turned upside down, so that the cope side of both pattern and flask was up. Parting sand was sprayed on the pattern with a cloth bag. The sprue with pouring cup incorporated at its top was then positioned into a blind hole previously drilled in the runner about 3/4" from the one end. The cope flask was then loaded with mix from the muller and hand rammed. The mixture in the corner near the sprue was then rammed with an iron rod. Care was taken to see that the mixture was also pushed around the gates (at the flask thickness).

The cope half was then rapped from all the four sides and drawn till it came out of the aligning pins, then it was placed on a wooden board. The pattern was lightly rapped by the rammer and drawn till it separated from the drag half and then placed aside.

(b) CO_2 Injection:

The CO_2 process of curing molds was selected in this investigation due to its several advantages. They are:

1. The short time required to develop sufficient and consistent hardness is a most important advantage over the conventional methods for dry sand molds which requires hours of baking cycle.

2. The absence of moisture in the mold controls this source of variation in the investigation.

3. Relatively long storage life as compared to other sand molds.

The cope and drag halves were separately cured with a CO_2 kit shown in photograph 1 (Appendix III). The CO_2 gas was injected into each mold half with a line pressure of 40 psi, through a rubber cup, at five locations (center and four corners) on both sides for about five seconds (± .5 sec.) at each location.

(c) Mold Storage:

After the CO_2 gassing cycle, the mold halves were aligned, and placed on a flat surface to minimize discrepancies in levelling of the mold from test to test. The top of the cope half was covered with a wooden board. The completed molds were stored approximately 20-22 hours before pouring was done. It has been reported that the CO_2 molds will develop a strength over some period of time (see fig. 15, Lange and Morey[31]) and then starts deterioration due to absorption of moisture by the hygroscopic material from the atmosphere[31].

The hardness of the molds was not measured because of the unavailability of the instrument for measuring CO_2 mold hardness, and was assumed to be uniform for all test molds.

C. Preparation of Molten Metal:

(a) Charging of Furnace:

The revecon oil-fired reverbaratory furnace was preheated for about thirty minutes. Eight to ten pounds of Aluminum-12 percent silicon was charged through the tapping spout onto the hearth and approximately sixty pounds of the same kind of pig was charged through the stack opening. At the same time two-thirds pound of commercial aluminum cover flux was charged into the furnace. The direct flame was adjusted to neutral one and the tapping spout was closed.

(b) Degassing of Melt:

The metal was melted and superheated to approximately 150° above the desired pouring temperature. The furnace was shut off.

The tapping spout was opened, and one commercial solid chloride-base degassing tablet was submerged and moved around in the melt. The decomposition of the chloride tablet liberated chlorine gas which reacted with melt and served to remove hydrogen gas from it. Two-thirds pound of aluminum cover flux was charged into the furnace at the same time. The melt was then allowed to lay for about three minutes.

Then, the melt was skimmed in the furnace and poured into a previously cleaned and preheated shank-type transfer ladle. This procedure was rigidly followed for each replication, to control the entrapped hydrogen gas and its effect on the metal flow. The furnace was cleaned with two-thirds pound of flux after each melting cycle.

D. Pouring of Metal and Recording of Data:

To eliminate the effect of variation in pressure head on the gate velocities, it was decided to reject the initial metal till the system attains steady state condition, and collect the metal flowing during the steady state to go into the final results.

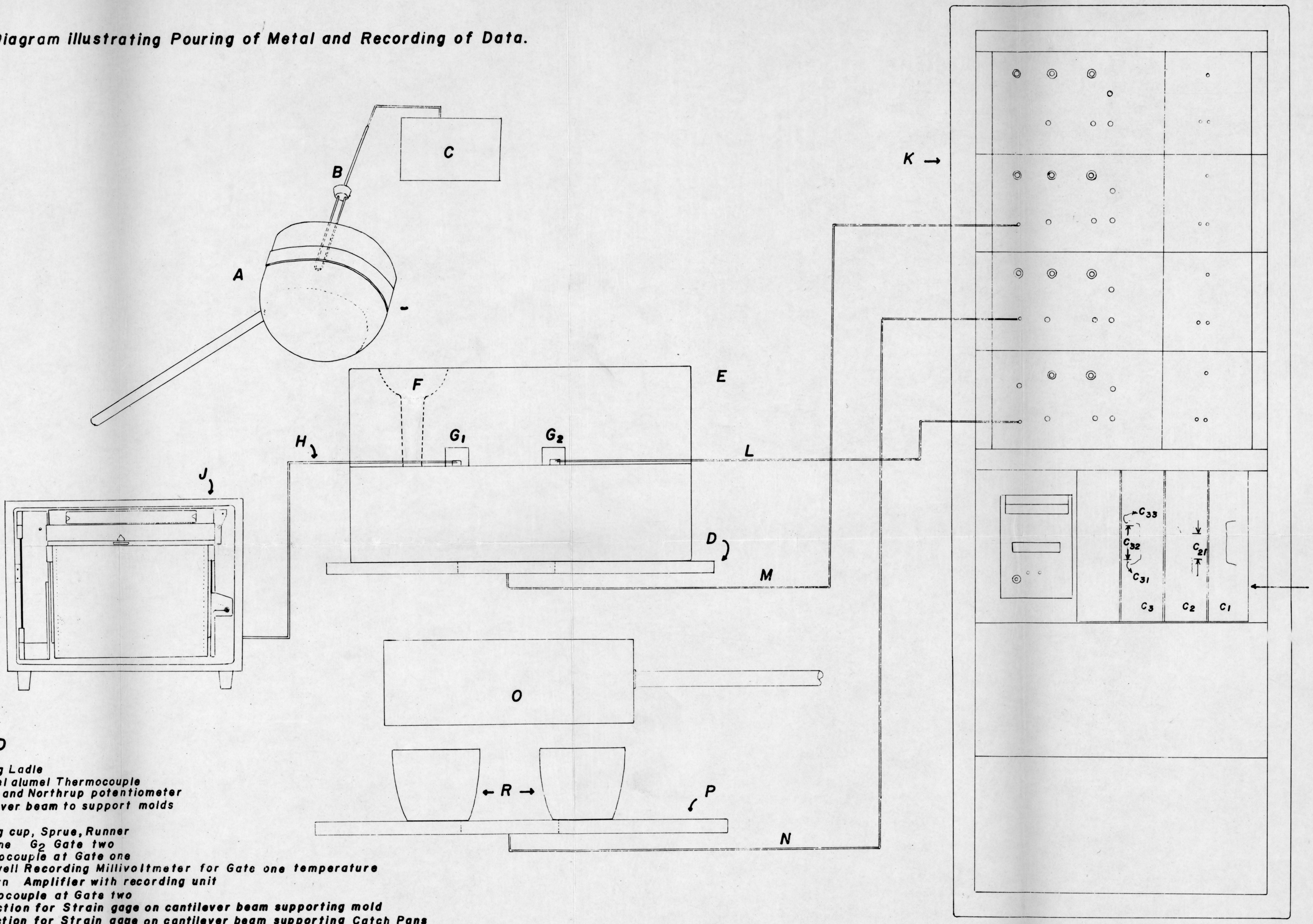
A schematic diagram for the pouring of metal and recording of data is shown in fig. 12.

In each replica, three molds in each of the pressurized and unpressurized gating systems were poured from the ladle at approximately 1550°F., 1450°F., and 1350°F., so that, by the time the system attains steady state condition, the thermal gradient between the mold and the metal is equalized.

The temperature of the metal in the ladle (fig. 12,A) was measured by a chromel-alumel thermocouple (fig. 12,B) connected to a Leeds and Northrup potentiometer (fig. 12, C), and the temperature of the metal emerging from the gates (fig. 12,G_1 and G_2) was measured by two chromel-alumel thermocouples (fig. 12, H and L) connected to a Sanborn amplifier with recording unit (fig. 12,K), and a recording Honeywell millivoltmeter (fig. 12,J).

When the metal in the ladle had dropped to a temperature of about 10°F. higher than the desired pouring temperature, the surface of the melt was carefully and quickly skimmed, then poured manually into the pouring basin (as shown in fig. 12) from a height of 1 -

Fig.12 Diagram illustrating Pouring of Metal and Recording of Data.



LEGEND

A Pouring Ladle
B Chromel alumel Thermocouple
C Leeds and Northrup potentiometer
D Cantilever beam to support molds
E Mold
F Pouring cup, Sprue, Runner
G_1 Gate one G_2 Gate two
H Thermocouple at Gate one
J Honeywell Recording Millivoltmeter for Gate one temperature
K Sanborn Amplifier with recording unit
L Thermocouple at Gate two
M Connection for Strain gage on cantilever beam supporting mold
N Connection for Strain gage on cantilever beam supporting Catch Pans
O Waste Metal Pan
P Cantilever beam supporting Catch Pan
R Catch Pans
S Recording Paper
  C_1 Channel Recording Temperature at Gate two
  C_2 Channel Recording Time
    C_{21} Time of Flow
  C_3 Channel for Indication of Steady and Unsteady State Conditions
    C_{31} Initial Unsteady State Condition
    C_{32} Steady State Condition
    C_{33} Final Unsteady State Condition

3 in. The metal entering pouring basin increased the weight on the cantilever beam, thus increasing strain on it. This was indicated by increased deflection of the stylus of the corresponding channel of the Sanborn amplifier (as shown by C_{31} (s), fig. 12) to which the strain gages on the beam were connected. This initial metal was collected in a separate pan, as shown by photograph 7, Appendix III, and did not enter into calculations. As the mold was filled up to the top of the pouring basin the weight on the cantilever beam became almost constant, which was indicated by the constant maximum deflection of the stylus (as shown by C_{32} (s), fig. 12). At this time, the metal was allowed to flow into the catch pans placed below gates on another cantilever beam with strain gages (as shown in fig. 12).

As the metal was allowed to flow into the catch pans; due to its impact, the stylus of the corresponding channel of the Sanborn unit connected to the strain gages on this beam was set into violent motion. Due to this the stylus did not leave a dark mark on the recording paper at any particular point. Thus, the starting of the very faint mark (as shown by C_2 (s), fig. 12) on the paper marked the starting point of catching the steady state metal. This continued while the metal was flowing into the pan. When the metal in the pouring ladle was about to finish, the waste metal pan was brought in to collect the final metal (shown by C_{33} (s), fig. 12), thus assuring only steady state metal enters into the final results.

At this time, the stylus became steady and marked the end point of catching the steady state metal with the continuation of dark line (as shown in C_2 (s), fig. 12). The time of flow was determined from the speed of the recording paper which was set at 1/4 ft./min. and the distance between the above two points (as shown by C_{21} (s), fig. 12).

E. Velocity Determination:

The solidified metal was removed from the container, weighed in air and in water on Troyner's portable scale. Then, by water displacement method volume of metal in cu. ft. was determined. This was then divided by the time of flow and respective gate areas to get the velocity of metal through each gate. According to $Q = A_1V_1$; i.e. $Q =$ ft.^{3}/sec.

$A_1 =$ ft.^{2}

$V_1 =$ ft./sec.

CHAPTER VI

DISCUSSION OF RESULTS

I. FIRST PRELIMINARY INVESTIGATION

The results of pouring eutectic aluminum - 12 percent silicon alloy in CO_2 mold showed that:

1. Due to large gate exit area it was not possible to fill the metal to the top of the sprue, thus not allowing the system to attain the steady state condition.

2. The response of the welded hot junction of the thermocouple was not rapid enough for the short pouring cycle.

II. SECOND PRELIMINARY INVESTIGATION

Necessary changes were made as a result of first preliminary investigation. With these changes second preliminary investigation consisted of pouring the eutectic aluminum-12 percent silicon alloy into pressurized and unpressurized CO_2 molds. The difficulties encountered and the respective corrections made are:

1. Because of the possibility of human error in clicking the switch, more precise time measuring device was needed.

Hence, it was decided to use a second cantilever beam with strain gages to support the catch pans, for measuring the time more precisely.

2. Because of the unknown and different loss of heat of metal while flowing from pouring cup to the gates from test to test, it

was not possible to obtain the desired same temperatures, namely, 100°F., 200°F., and 300°F. degrees superheat of the metal emerging from each gate.

Hence, it was decided to pour the metal from the ladle at 1550°F., 1450°F., and 1350°F., and measure the temperature of the metal emerging from each gate and use a statistical design to correct for the deviation of the observed temperature from the desired ones.

III. FINAL INVESTIGATION

The information gained in second preliminary investigation enabled a more effective testing procedure to be followed in the final investigation.

During the first replication of the final investigation 4 out of 6 temperatures at gate two were not recorded correctly because of (i) improper contact between metal and thermocouple (2 times), and (ii) burning of the twisted end of the thermocouple (2 times).

From the second preliminary investigation it was found that the temperature at two gates are not the same, but the difference was nominal (range 7-22°F. and average 14°F.). Therefore, the author decided to use the temperature of gate one for carrying out the statistical analysis of the final results, assuming that the difference in temperature between two gates has no effect on final results. The assumption is supported by the statistical analysis of the results which show that superheat (100-300°F.) has no significant effect on velocities of aluminum-12 percent silicon alloy through each gate in pressurized and unpressurized gating systems in CO_2 molds.

A. Statistical Analysis of Results:

It was not possible to obtain the desired same temperature of the metal emerging from each gate. To correct for the discrepancies of the observed temperature from the desired values, viz; 100°F., 200°F., and 300°F. degrees superheat it was decided to use co-variance analysis, which adjusts for this difference. But after the calculations were made, the regression coefficients were found to be non-significant ($F < 1$). This implies the adjustments are very poorly estimated and would decrease the accuracy of the analysis if applied. Hence, unadjusted mean squares were used for testing the hypotheses.

Analysis of variance technique was employed to analyze the results obtained.

The analysis of variance, separates the total variation in a set of data into parts, each part measuring variability attributable to some specific source or treatment. This technique estimates how much of the total variation is attributable to one or more assignable causes of variation. The remaining variation, not attributable to any assignable cause, is termed the residual or error variation. When applying this analysis to a process, this error variation would be the process variation. The error variation then, is the variation due to the method of experimentation. The assignable cause variation due to some treatment which causes a significant change in the pattern of variation and causes the sample to belong to some distribution other than that of the parent distribution.

The first step in the statistical analysis of the results was to calculate the sum of squares (S.S.) that can be attributed to different sources. Dividing the sum of squares by their respective degrees of freedom gives the mean square (M.S.), which is an estimate of the standard deviation that can be attributed to each source.

The physical meaning of degrees of freedom can best be explained by an example. In the identity $\sum_{i=1}^{N} (X_i - \bar{X}) = 0$, if N-1 of the $(X_i - \bar{X})$ are known, the remaining one is automatically determined. Thus, the number of degrees of freedom for N variables may be defined as the number of independent comparisons that can be made with the N variables.

The next step was the test of significance, to decide whether any assignable cause variation exists or the variation is the result only of experimental error. For these tests, the statistic,

$$F = \frac{\text{Mean square for Treatments}}{\text{Mean square for Error}}$$

is used in testing the hypothesis that the treatment effects are equal to zero. This ratio follows a particular F-distribution which is defined by certain degrees of freedom for that curve.

One tail-end of the total F-distribution is marked off which decides: whether the sample F-ratio is indicative of the parent F-distribution curve or not, and within what limits can the sample F-value fall and be representative of the parent F-distribution curve. This marked off portion is called the critical region (See fig. 13).

When the value of the F-statistic falls within the critical region (ratio greater than 4.0 in fig. 13) of the F-distribution for the corresponding degrees of freedom, the hypothesis that the treatment effects are equal to zero is rejected. If the F-statistic fall outside the critical region (ratio less than 4.0 in fig. 13), then the hypothesis that the treatment effects are equal to zero is not rejected. Similarly the effect of other variables and the interactions between them can be tested.

When making an inference about a particular F-distribution curve from a given sample value, one may reject the hypothesis erroneously. This is called a Type I error. This percentage of all possible samples leading to the committing of a Type I error is called the significance level. Consequently, the significance level is the probability that a Type I error may be committed on the basis of a single sample.

The significance level is arbitrarily chosen. In practice, 5 percent and 1 percent significance levels are usually chosen and once selected determine the critical region for a particular F-distribution curve.

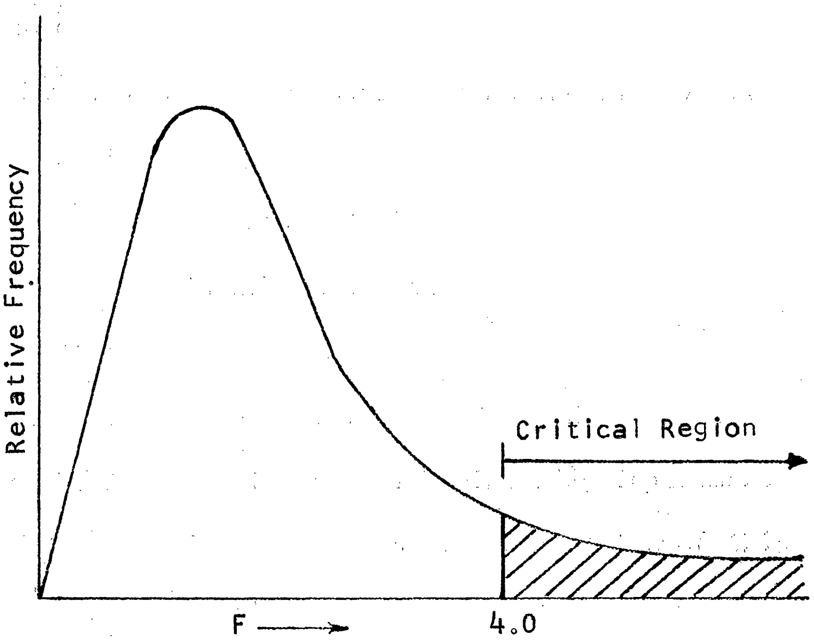


Fig. 13 F-distribution

Results of the analysis of variance for the data in Appendix I are shown in table 1.

A sample calculation of results is shown in Appendix II.

B. Interpretation:

For the pressurized (Gating Ratio 4.92 : 2 : 1) and unpressurized (Gating Ratio 1 : 3.33 : 1.67) gating systems (for details see figs. 9, 10, 11, 12), with two 3 in. long rectangular gates (Gate one: 3 5/8 in. from the sprue, area 1/8 $in.^2$; Gate two: 7 1/8 in. from the sprue, area 17/128 $in.^2$), spaced 3 1/2 in. apart, the results of superheat (100-300°F.) effect on gate velocities of aluminum 12-percent silicon alloy in CO_2 molds, were interpretated statistically for the following effects:

Replication Effects (Effect of Different Furnace Heats):

From table No. 1 it could be said that statistically the effects of different furnace heats (new, first, second and third remelts) were not significant. That is, the hypothesis that there are no effects of different furnace heats on velocities of aluminum -12% silicon through both gates in pressurized and unpressurized gating systems in CO_2 molds, was accepted.

Pressure Effects:

From table No. 1 it could be said that statistically the effects of pressure were highly significant. That is, the hypothesis that pressurized and unpressurized gating systems have no effects on the velocities of aluminum -12 percent silicon, through both gates, in CO_2 molds, was rejected.

From the sample calculations, table for R x P (p.) pressurized

TABLE 1

ANALYSIS OF VARIANCE TABLE FOR GATE VELOCITIES

Source	d.f.	SS_{xx}	SP_{xy}	SS_{yy}	Adjusted SS	d.f.	M.S.	F-Ratio	Remarks
Replications	3	4157.58	70.154	1.2289	.7764	3	.2588 *.4096	.9653 *1.759	NS NS
Pressure (P)	1	6.75	11.239	18.7150	18.8731	1	18.8731 *18.7150	70.396 *80.3908	BS HS
Error (a)	3	1096.23	-13.331	0.6984	0.5363	2	0.2681 *0.2328		
Temperature (T)	2	5826.50	80.127	1.1330	1.3981	2	0.6990 * .5665	1.0406 *0.9005	NS NS
Pressure x Temp.	2	1263.50	-24.964	1.2030	0.9915	2	0.4957 * .6015	0.7395 *0.9561	NS
Error (b)	12	10356.70	-40.800	7.5497	7.3890	11	0.6717 *0.2392		
Gates (G)	1	0.00	00.000	1.0470	1.0470	1	1.0470	64.62	HS
Pr. x Gates	1	0.00	00.000	0.0079	0.0079	1	0.0079	.49	NS
Temp. x Gates	2	0.00	00.000	0.0243	0.0243	2	0.0121	.75	NS

Table I (contd).

Source	d.f.	SS_{xx}	SP_{xy}	SS_{yy}	Adjusted SS	d.f.	M.S.	F-Ratio	Remarks
Pr.xTemp.xGates	2	0.00	0.00	0.0159	0.0159	2	0.00795	.49	NS
Error (c)	18	0.00	0.00	0.2923	0.2923	18	0.0162		
Total	47	22707.26	82.425	31.9084					

* Values obtained after finding the regression coefficient non-significant

NS = Non-significant

BS = Barely significant i.e. significant at 1% level of significance and non-significant at 5% level of significance

HS = Highly significant

gating system has higher velocities than the unpressurized system. The average increase in gate velocities of pressurized system is (75.8880 - 45.9160)/24 = 1.249 ft./sec. The standard deviation, i.e. deviation of the observations from the mean (from table 1) is $\sqrt{\frac{2 \times .2328}{24}}$ = .1373 ft./sec.

Superheat Effects:

From table No. 1 it could be said that statistically the effects of superheat (100-300°F.) were not significant. That is, the hypothesis that there are no effects of different degrees (100-300°F.) of superheat on velocities of Aluminum - 12 percent silicon in pressurized and unpressurized gating systems in CO_2 molds was accepted.

Gates Effects:

From table No. 1 it could be said that statistically the effects of gates were highly significant. That is, the hypothesis that there are no effects of gate location on gate velocities of aluminum 12-percent silicon, through both gates in pressurized and unpressurized gating systems in CO_2 molds was rejected.

From the table II, Appendix II, gate two (farther from the sprue) has higher velocity than the gate one (near the sprue). The average increase in velocity from table III, Appendix II, is 7.0892/24 = .295 ft./sec. The standard deviation, i.e. deviation of observations from the mean (from table 1) is

$$\sqrt{\frac{2 \times .0162}{24}} = .03676 \text{ ft./sec.}$$

Interaction Effects:

From table No. 1 it could be said that statistically the interaction effects of (i) pressure and superheat, (ii) superheat and gates, (iii) gates and pressure, and (iv) pressure, superheat and gates, were not significant. That is, the hypothesis that there is no interaction effects (additional effects due to combined influence) of (i) pressure and superheat, (ii) superheat and gates, (iii) gates and pressure, and (iv) pressure, superheat and gates, on the velocities of aluminum - 12 percent silicon through both gates in pressurized and unpressurized gating systems in CO_2 molds, was accepted. This means that all the three variables (pressure, superheat, and gates) are independent of each other.

C. Discussion:

The testing procedure presented in this thesis seems adequate for the investigation of the superheat effect on gate velocities of aluminum -12 percent silicon alloy in pressurized and unpressurized gating systems, in CO_2 molds. The conclusion is based on the statistical interpretation in preceding section; wherein it was determined that the type of gating system (pressurized or unpressurized) and individual gate location have significant effect, whereas superheat (100-300°F.) has no significant effect on gate velocities of aluminum -12 percent silicon alloy in CO_2 molds. The conclusions substantiate those made by past investigations of metal flow in green sand molds. The results also show that the three variables (pressure, superheat and gates location) are independent of each other, and that different furnace heats have no significant effect on velocities of aluminum -12 percent silicon through each gate in pressurized and unpressurized gating systems in CO_2 molds. However, comments must be made in regard to the conclusion about different furnace heats. Originally, new commercial Alcoa Aluminum - 12% silicon ingots were charged into the furnace. The second melting was accomplished using the foundry returns of the first melt. Then the third melting was performed on the second melt returns plus an addition of Al - 12% silicon scrap (no. of remelts unknown). The fourth melting was done on this third melt return without further addition. The scrap additions were made because of melting losses from the first and second melts and an inadequate supply of new ingots. It is doubtful that this introduced an error but the author feels he should state there is this possibility. Agee[2] has found remelting has no statistical effect on the fluidity of Al-silicon alloys in CO_2 molds.

Table IV shows the flow rates through each gate in a pressurized gating system. From this table it is evident that for 200 and 300°F. superheat, two out of four replications and for 100°F. all the four replications show almost equal flow rate through each gate. From these results it may be concluded that law of continuity ($Q = A_1V_1 = A_2V_2$) may be approximately applied to pressurized gating systems poured at 200 and 300°F. superheat and more accurately for 100°F.

superheat.

The method and procedure presented in this investigation involves three important features:

1. Rejection of the damaged metal from the initial part of the pour, thereby minimizing defects in castings.

2. Equalization of the thermal gradient between the metal and the mold, by the time the metal enters the mold cavity. Thus, reducing the rate of heat transfer from metal to mold which can be used to produce an even temperature distribution in the casting.

3. Constant pressure head which can be an aid in applying hydraulic laws to the gating systems for estimating velocity of flow and thereby controlling the metal flow.

These and the discussion on metal flow through different parts of a gating system with a minimum of turbulence, gas aspiration, dross formation and the discussion of hydrodynamic principles relating to gating system should be an aid in designing the gating system and the consequent production of sound and finished castings.

D. Recommendations:

As a result of this investigation the author recommends the following for further investigation of metal flow in gating systems:

1. The sprue be positioned midway between the two gates so that equal heat loss from sprue exit to gate exit may be expected with the consequent possibility of equal temperature of metal emerging from each gate.

2. The speed of the recording paper may be increased to correct for the discrepancy which may take place in determining the distance on the recording paper as a measure of time for metal flow.

3. The split-split-plot design may be similarly used to investigate the effect of other variables, e.g. different metal compositions; different gating systems with different gating ratios; etc., on the gate velocities of metal through pressurized and unpressurized gating systems (all molds poured at constant degrees superheat).

4. The idea of measuring temperature at the ladle and at the gates may be used as a step towards determining frictional and other losses during the flow of metal.

CHAPTER VII

CONCLUSIONS

For the pressurized (Gating Ratio: 4.92 : 2 : 1) and unpressurized (Gating Ratio: 1: 3.33 : 1.67) gating systems (for details see fig. 7, 8, 9, 10), with two 3 in. long rectangular gates (Gate one: 3 5/8" from the sprue, area, 1/8 in.^{2}; Gate two: 7 1/8" from sprue, area 17/128 in.^{2}), spaced 3 1/2 in. apart, the results of superheat (100-300°F.) effect on gate velocities of aluminum 12 percent silicon alloy in CO_2 molds were analyzed statistically and it could be concluded that:

1. Remelting of metal charge (new, first, second, and third remelts) has no effect on the velocities of aluminum -12 percent silicon alloy through either gate in pressurized and unpressurized gating systems in CO_2 molds.

2. Pressurized and unpressurized gating systems have significant effect on velocities of aluminum -12 percent silicon through both gates in CO_2 molds. The pressurized system has higher gate velocities than the unpressurized system. The average increase in gate velocities of pressurized system is 1.249 ft./sec. with a standard deviation (deviation of the observations from the mean) of .1393 ft./sec.

3. Different degrees of superheat (100-300°F.) have no significant effect on velocities of aluminum -12 percent silicon through either gate in pressurized and unpressurized gating systems in CO_2 molds.

4. The position of gates has a highly significant effect on gate velocities of aluminum -12 percent silicon, through each gate in pressurized and unpressurized gating systems in CO_2 molds. Gate farther from the sprue (Gate two) has higher velocity than the gate near the sprue (Gate one). The average increase in velocity is .295 ft./sec. With a standard deviation (deviation of the observations from the mean) of .0368 ft./sec.

5. There is no interaction effects (additional effect due to combined influence) of (i) pressure and superheat, (ii) superheat and gates, (iii) gates and pressure, and (iv) pressure, superheat, and gate, on velocities of aluminum 12-percent silicon through both gates in pressurized and unpressurized gating systems in CO_2 molds. That is all the three variables (pressure, superheat, and gates) are independent of each other.

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APPENDIX

APPENDIX I

NOMENCLATURE:

P_1 = Pressurized Gating System

P_2 = Unpressurized Gating System

T_1 = Temperature (300°F. superheat)

T_2 = Temperature (200°F. superheat)

T_3 = Temperature (100°F. superheat)

G_1 = Gate 1

G_2 = Gate 2

X = Difference in Temperature from the desired degrees of superheat (observed - desired)

Y = Velocity

TABLE II

DATA OBTAINED FOR INVESTIGATION OF SUPERHEAT EFFECT ON GATE VELOCITIES

Rep. No.	Gates	P_1						P_2					
		T_1		T_2		T_3		T_1		T_2		T_3	
		X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
1	G_1	-3	2.5414	46	3.5000	0.00	2.5154	19	1.7228	11	1.9972	51	1.6849
	G_2	-3	3.0712	46	4.2313	0.00	2.7475	19	2.2925	11	1.9780	51	1.7441
2	G_1	-3	3.0489	15	3.3872	30	2.5263	-3	1.4063	7	1.6665	34	1.8259
	G_2	-3	3.3650	15	3.7682	30	2.8408	-3	1.6612	7	2.0448	34	1.8513
3	G_1	6	1.7012	46	2.4981	0.00	4.0464	-37	1.9852	46	1.7120	0.00	1.6242
	G_2	6	1.9377	46	2.6196	0.00	4.1864	-37	2.2487	46	2.0980	0.00	2.0506
4	G_1	32	2.8559	28	3.2668	43	4.1309	23	1.9429	37	1.8844	43	1.8866
	G_2	32	3.1242	28	3.5931	43	4.3845	23	2.2199	37	2.0840	43	2.3040

TABLE III

DIFFERENCE IN GATE VELOCITIES (GATE TWO-GATE ONE)

Rep. No.	P_1				P_2				
	T_1	T_2	T_3	ΣT	T_1	T_2	T_3	ΣT	
1	0.5298	0.7313	0.2321	1.4932	0.5697	-0.0192	0.0592	0.6097	
2	0.3161	0.3810	0.3145	1.0116	0.2549	0.3783	0.0254	0.6586	
3	0.2365	0.1215	0.1400	0.4980	0.2635	0.3860	0.4264	1.0759	
4	0.2683	0.3263	0.2536	0.8482	0.2770	0.1996	0.4174	0.8940	
Totals				3.8510				3.2382	Grand Total = 7.0892

TABLE IV

FLOW RATES IN PRESSURIZED GATING SYSTEM

Superheat	Rep. No.	Flow Rate in ft^3/sec.	
		Gate-one	Gate-two
300°F.	1	.002344	.002666
	2	.001297	.001442
	3	.001569	.001682
	4	.002634	.002712
200°F.	1	.003228	.003673
	2	.001537	.001775
	3	.002304	.002274
	4	.003013	.003119
100°F.	1	.002320	.002385
	2	.001684	.001607
	3	.003732	.003634
	4	.003810	.003806

APPENDIX II

SAMPLE CALCULATIONS

From the table No. II, the following two-way table of R x P was constructed:

	R_1	R_2	R_3	R_4	ΣP
P_1	18.6068	18.9364	16.9894	21.3554	75.8880
P_2	11.4195	10.4560	11.7187	12.3218	45.9160
ΣR	30.0263	29.3924	28.7081	33.6772	121.804

$$C.F. = \text{Correction Factor} = \frac{(121.804)^2}{48} = 309.0878$$

The sum of squares for replications

$$= \frac{(30.0263)^2 + \text{- - - - - - -} (28.7081)^2}{12} - C.F.$$

$$= 1.2289$$

The sum of squares for Pressures

$$= \frac{(75.8880)^2 + (45.9160)^2}{24} - C.F.$$

$$= 18.7150$$

The sum of squares for 8 plot Totals

$$= \frac{(18.6068)^2 + \text{- - - - - - - -} (12.3218)^2}{6} - C.F.$$

$$= 20.6423$$

The sum of squares for Error (a)

= Sum of squares for totals - s.s. of replications

- s.s. of pressures

= 20.6423 - 1.2289 - 18.7150

= 0.6984

From the Table II, the following three way table was prepared:

Rep No.	Pressure	T_1	T_2	T_3
1	P_1	5.6126	7.7313	5.2629
	P_2	4.0153	3.9752	3.4290
2	P_1	6.4139	7.1554	5.3671
	P_2	3.0675	3.7113	3.6772
3	P_1	3.6389	5.1177	8.2328
	P_2	4.2339	3.8100	3.6748
4	P_1	5.9801	6.8599	8.5154
	P_2	4.1628	3.9684	4.1906
Totals	Σ R P_1	21.6455	26.8643	27.3782
	Σ R P_2	15.4795	15.4649	14.9716
	Σ R	37.1250	42.3292	42.3498

The s.s. for Temperatures

$$= \frac{(37.1250)^2 \; + - - - - \; (42.3498)^2}{16} \; - \text{C.F.}$$

$= 1.1330$

The sum of squares for 6 plot totals

$$= \frac{(21.6455)^2 \; + - - - - - - + \; (14.9716)^2}{8} - \text{C.F.}$$

$= 21.2510$

The s.s. for subtotals

$$= \frac{(5.6126)^2 + - - - - - \; (3.6772)^2}{2} - \text{C.F.}$$

$= 30.7280$

The pressure x temperature sum of squares

= s.s. of 6 plot totals - s.s. for pressures

$= 21.2510 - (18.7150 + 1.3330)$

$= 1.2030$

The sum of squares for error (b)

= s.s. of subtotals - (s.s. of 6 plot totals + s.s. of temperature + s.s. of temp x pressure)

$= 30.7280 - (20.6423 + 1.3330 - 1.2030)$

$= 7.5497$

From the Table II, the following two-way of temperature x gates was prepared:

	T_1	T_2	T_3	Σ G
G_1	17.2046	19.9122	20.2406	57.3574
G_2	19.9204	22.4170	22.1092	64.4466

The s.s. for gates,

$$= \frac{(57.3574)^2 + (64.4466)^2}{24} - C.F.$$

$$= 1.0470$$

The s.s. for 6 plot Totals,

$$= \frac{(17.2046)^2 + - - - - - (22.1092)^2}{8} - C.F.$$

$$= 2.2043$$

The s.s. for temperature x gates

= S.S. for 6 plot totals - s.s. for temperature
- s.s. for gates

$$= 2.2043 - 1.1330 - 1.047$$

$$= 0.0243$$

Also the following two-way table was prepared from Table II:

	P_1	P_2
G_1	36.0185	21.3389
G_2	39.8695	24.5771

The sum of squares for 4 plots,

$$= \frac{(36.0185)^2 + - - - - - (24.5771)^2}{12} - \text{C.F.}$$

$= 19.7699$

The s.s. for pressure x gates,

= s.s. for 4 plots - s.s. for pressure - s.s. for gates

$= 19.7699 - 18.7150 - 1.0470$

$= .0079$

From the Table II, the following three-way table was prepared:

	P_1			P_2		
	T_1	T_2	T_3	T_1	T_2	T_3
G_1	10.1474	12.6521	13.2190	7.0572	7.2601	7.0216
G_2	11.4981	14.2122	14.1592	8.4223	8.2048	7.9500

The sum of squares for the subtotals,

$$= \frac{(10.1474)^2 + - - - - - - + (7.9500)^2}{4} - \text{C.F.}$$

$= 22.3461$

The s.s. for P x T x G

= s.s. for the subtotals - (S.S. for P + S.S. for T + S.S. for P x T + S.S. for G + S.S. for T x G + S.S. for P x G)

$= 22.3461 - (18.7150 + 1.1330 + 1.2030 + 1.0470 + 0.0243 + .0079)$

$= .0159$

From table No. 11, the grand total sum of squares

$$= (2.5414)^2 + - - - - - - - + (2.3040)^2 - \text{C.F.}$$

$$= 32.1154$$

The s.s. for error (c)

= s.s. of grand total - (s.s. for subtotals
+ s.s. for error (a)
+ s.s. for error (b)
+ s.s. for Reps

$$= 32.1154 - (30.7280 + 1.0470 + 0.0243 + .0079 + .0159)$$

$$= .2923$$

The sum of squares were calculated as above, and entered in table 1. These s.s. were then adjusted using the formula. Adjusted s.s. = $SS_{yy} - (SP_{xy})^2 / SS_{xx}$, due to this there was a loss of 1 d.f. for error (a) and error (b). The adjusted s.s. were then divided by d.f. to get mean square. Test was then made for the significance of the regression coefficient as follows:

For Error (a),

$$F \text{ for Reg. coef.} = \frac{0.6984 - 0.5363}{.2681} = .6046$$

For Error (b)

$$F \text{ for Reg. coef.} = \frac{7.5497 - 7.3890}{.6717} = .2392$$

Thus, both the regression coefficients were found to be non-significant (value less than 1). Hence, it was decided to use unadjusted sum of squares.

Therefore, the calculated sum of squares were divided by respective degrees of freedom to give the mean squares, which is an estimate of the standard deviation attributable to each source.

The next step is to see if any assignable cause of variation exists. The hypothesis to be tested as follows:

H_o : There is no difference in gate velocities for different pressures in gating system (pressurized or unpressurized gating system)

H_1 : There is difference in gate velocities for different pressures in gating system (pressurized or unpressurized gating system)

$$F \text{ calculated} = \frac{\text{Mean square for Pressure}}{\text{Error mean square}}$$

$$= \frac{18.7150}{0.2328}$$

$$= 80.3908$$

From the F distribution tables

$$F_{0.95}\ (1,3) = 10.13$$

$$F_{0.99}\ (1,3) = 34.12$$

Comparing F calculated and F tabulated, we found that F calculated is greater than F tabulated.

Reject the hypothesis that the gate velocities are same for different pressures in gating systems (pressurized or unpressurized gating system).

For finding out the F ratio for replication and pressure, error (a) mean square was used while for temperature and interaction of temperature with pressure, error (b) mean square was used. Error (c) mean square was used for finding out the F ratio for gates, interaction of gates with pressure, interaction of gates with temperature, interaction of gates with pressure and temperature.

After testing each of these sources of variation, we find the effects of pressure and gates to be significant. These sources of variation are then accountable for the significant treatment variation.

The following dimensionless values of F were obtained from F distribution tables:

$F_{0.99}$ (1,3) = 34.12

$F_{0.95}$ (1,3) = 10.13

$F_{0.99}$ (3,3) = 29.46

$F_{0.95}$ (3,3) = 9.28

$F_{0.99}$ (2,12) = 6.93

$F_{0.95}$ (2,12) = 3.88

$F_{0.99}$ (1,18) = 8.28

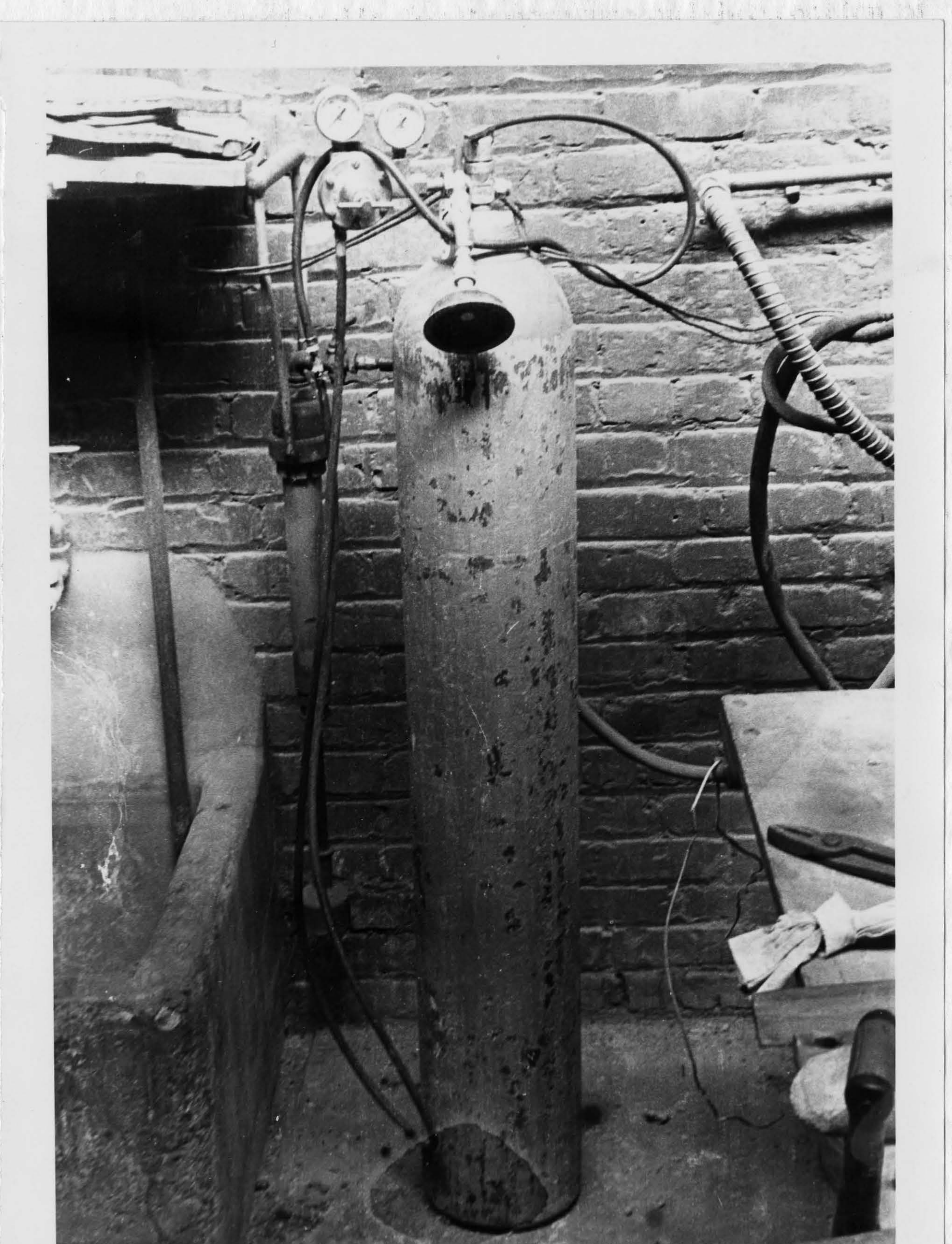
$F_{0.95}$ (1,18) = 4.41

$F_{0.99}$ (2,18) = 6.01

$F_{0.95}$ (2,18) = 3.55

APPENDIX III

Photograph 1



CO_2 Gassing Unit

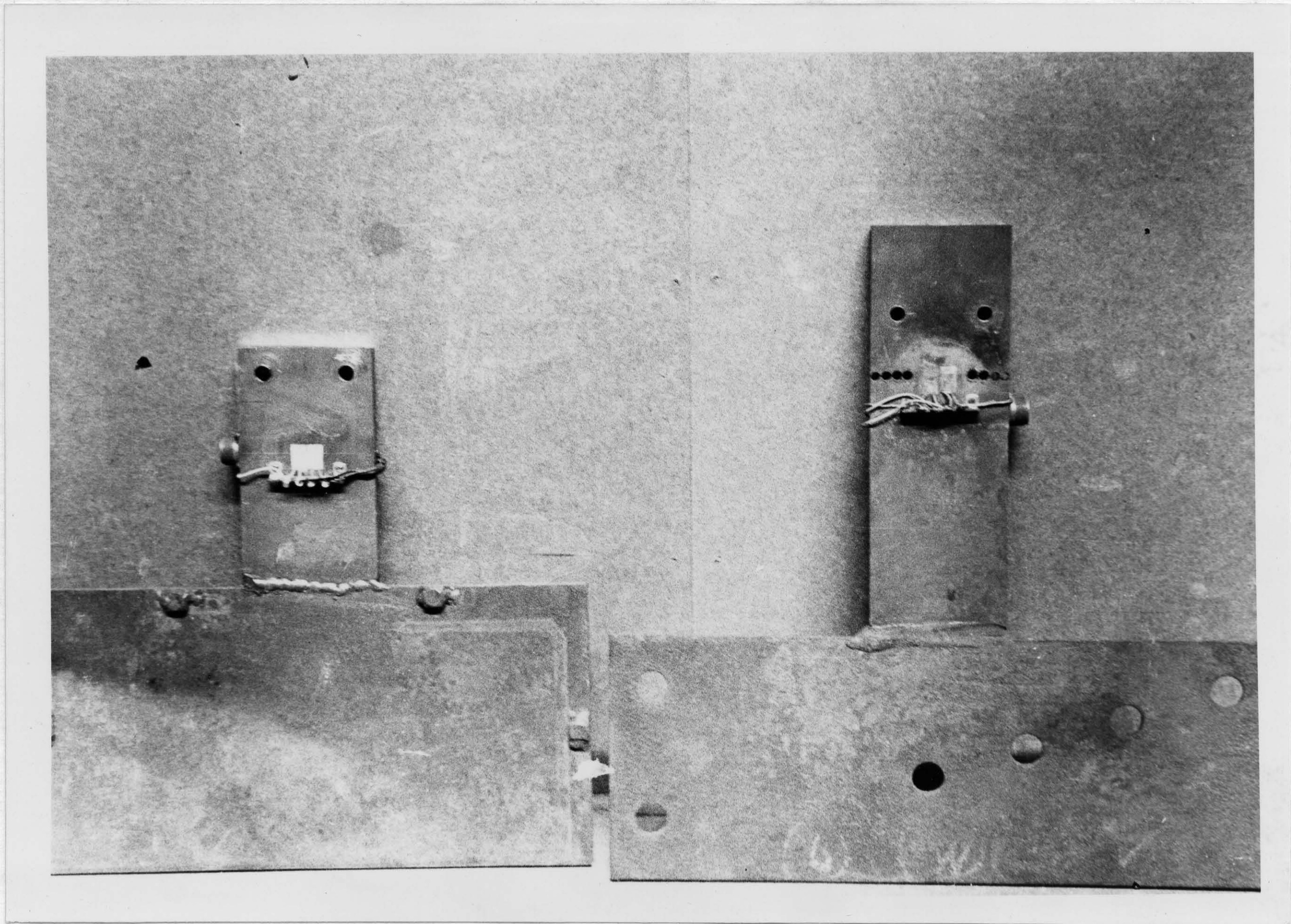
Photograph 2

Cope-Half of Pattern and Mold

Photograph 3

Drag-half of Pattern and Mold

(A) Photograph 4 (B)

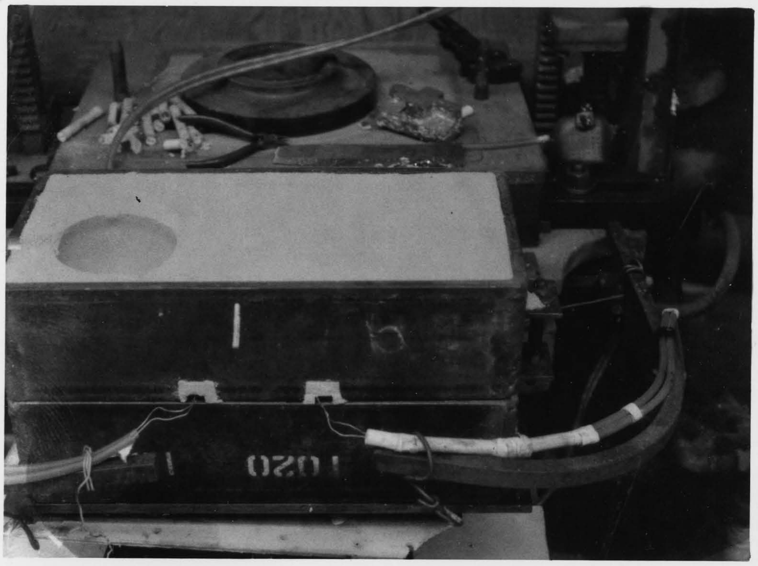


Cantilever Beams

(A) For Supporting Molds

(B) For Supporting Catch Pans

Photograph 5



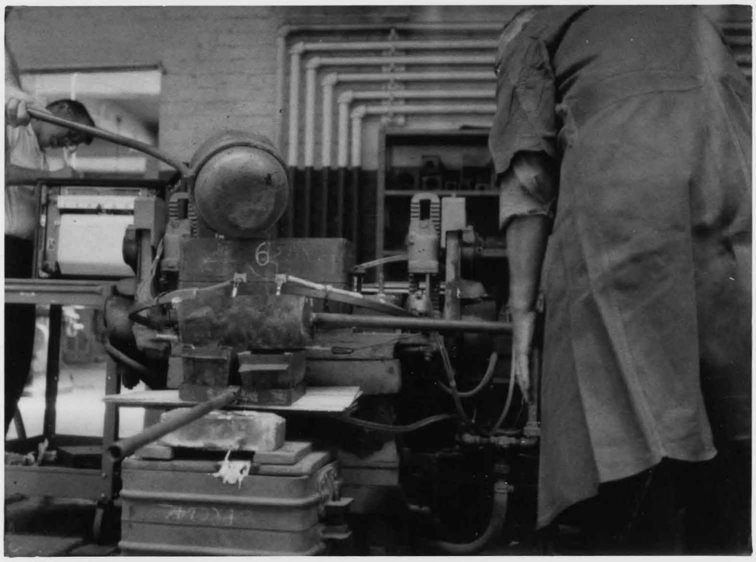
Mold Supported on Cantilever Beam

Photograph 6

Tapping of Metal from Furnace

⑧

Photograph 7



Catching of Initial Metal

Photograph 8

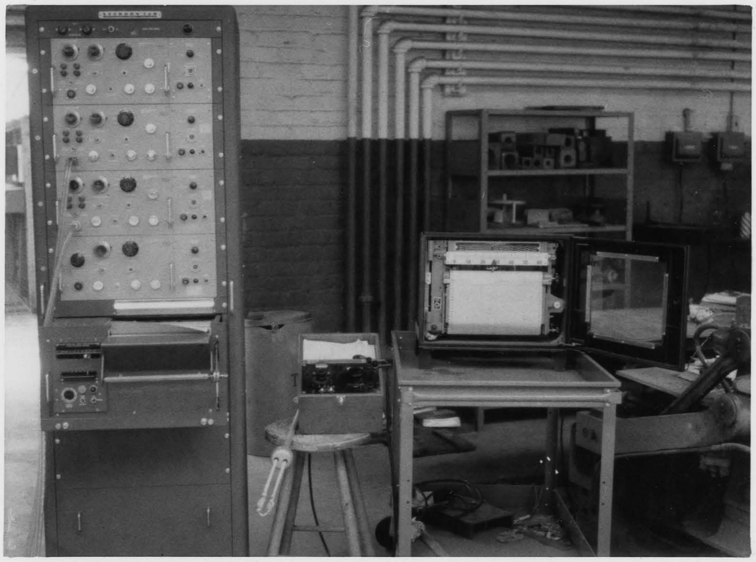
Catching of Steady State Metal

PS

Photograph 9

Catch Pans with Solidified Metal

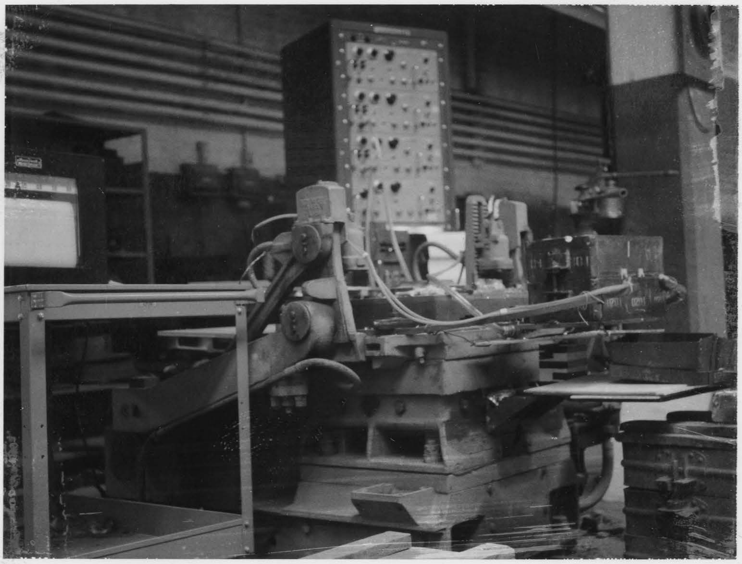
Photograph 10



Instrumentation used in Experiment

(75)

Photograph 11



Experimental Set-Up

ABSTRACT

The objective of this thesis investigation was to design an experiment to investigate superheat effect on gate velocities in pressurized and unpressurized gating systems each having two gates, and to analyze statistically any interrelationship between these variables in CO_2 molds.

A discussion on metal flow through different parts of a gating system, with a minimum of turbulence and gas aspiration, and a discussion of hydrodynamic principles relating to gating systems were given. The realization of these conditions is desirable because it results in improved castings, fewer rejects, and greater economy in a casting production. This was followed by a discussion on metal flow variables. Principle and use of instrumentation used in the experiment was discussed. Split-split-plot type of statistical design was used. Statistical analysis of results was made.

The author concluded that, the type of gating system (pressurized or unpressurized) and individual gate location have significant effect, whereas superheat (100-300°F.) has no significant effect on gate velocities of aluminum -12 percent silicon in CO_2 molds. Also, all the three variables are independent of each other.