

# Investment Casting Design of Experiment

Federal Manufacturing & Technologies

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INVESTMENT CASTING  
DESIGN OF EXPERIMENT

Robert Owens

Published October 1997

Final Report  
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# ABSTRACT

*Specific steps in the investment casting process were analyzed in a designed experiment. The casting's sensitivity to changes in these process steps was experimentally determined. Dimensional and radiographic inspection were used to judge the sensitivity of the casting. Thirty-six castings of different pedigrees were poured and measured. Some of the dimensional inspection was conducted during the processing. It was confirmed that wax fixturing, number of gates, gate location, pour and mold temperature, pour speed, and cooling profile all affected the radiographic quality of the casting. Gate and runner assembly techniques, number of gates, and mold temperature affect the dimensional quality of the casting.*

# SUMMARY

A cross-functional team was formed with members from FM&T Kansas City, the Fast Cast Facility at Sandia National Laboratory, and Amcast Corporation – an investment foundry in Rancho Cucamonga, CA. Through brainstorming, the team listed the desired impact of this study on the investment casting process. Generally, they were all related to on-time delivery or reduced defects. Each process step was weighed against the desired impact of the project.

It was agreed that if weld repair is eliminated or drastically reduced, most of the desired impacts could be realized. A design of experiment was conducted to investigate the relationship of those process steps responsible for weld repair to the quality of the final casting. Although most of the process steps were discussed, only 10 were incorporated into the experiment to keep the number of castings down to a tractable number. The process steps are gating assemblers, wax fixturing, number of gates, size of gates, location of gates, metal pour temperature, mold temperature, pour speed, pour operators, and cooling profile. Each one of these steps, called factors, was assigned a high or + value and a low or - value. These values were centered on the null value which was loosely based on the production history of the casting. In some cases such as operators, the values were simply each of the operator's names, and no high or low was intended.

The effects on the finished casting were measured by radiographic inspection and dimensional inspection. Radiographic inspection was conducted on the castings at FM&T's NDT lab. Defects were categorized per ASTM E192. Dimensional inspection was performed on the wax pattern just after injection, after a two-week dwell time, after the gates and runners were assembled, and at the casting level after rough removal of the gates. Flatness was measured at key locations of the castings on one particular coordinate measuring machine at Sandia National Laboratory, Albuquerque, NM. These key locations were chosen to highlight certain casting attributes. For example, the cantilevered sections were expected to slump in the unsupported configuration during the two-week dwell. Inspection of this surface should reveal the importance of supporting this cantilever section. We found the only factors that didn't affect the responses were pour operators and the size of the gates.

# DISCUSSION

## SCOPE AND PURPOSE

Investment castings produced by various outside foundries for FM&T have not met our expectations or those of our customers. Most people familiar with the investment process consider it to be more art than science. The trial and error methods used in today's foundries are too unreliable to support our efforts of timely delivery and zero defects.

This project was undertaken to methodically analyze the investment casting processes (factors) and determine their influence on particular aspects of the finished castings (responses). If some factors do not significantly influence the responses, the time and money spent to control them would be better used on factors that do influence the responses. These principles are in place at some foundries where easily measured factors such as wax injection temperature and pressures are being monitored and ultimately controlled. This is improving the product, but ultimately, only the tougher factors and responses will be left to investigate. These hard-to-measure factors probably influence the responses a great deal. Generally, steel castings are more difficult to produce than aluminum castings. During this experiment we concentrated on 17-4 stainless steel castings, although a lot of the processing steps also apply to aluminum castings.

## ACTIVITY

### The Team

The team consisted of people from FM&T, Sandia National Laboratory, and Amcast Corporation, an aerospace foundry in Rancho Cucamonga, CA. Sandia was included to tap their vast knowledge in casting and metal solidification. Their Fast Cast Facility was used for the bulk of the casting processing. Amcast was included for their expertise in investment casting and processing in a commercial aerospace foundry.

### Process Factors

In order to focus this experiment, the team discussed the desired impact of this project on the investment casting process. Included in this list of wants are:

- *Compress development time.*
- *Deliver a "to the print" casting in three iterations.*
- *Get a true lead time and early identification of pacing items.*
- *Reduce component variation.*
- *Find the limits and capabilities of the casting process.*
- *Receive perfect product on time.*
- *Examine the possible application of experimental design and statistical techniques to the casting process.*
- *Supply prototypes to the designers quickly.*

Next, we identified the major steps in the casting process and found which ones negatively affect the stated wants from above. The major steps are:

- a) *Design casting and die.*
- b) *Procure die*
- c) *Produce wax*
- d) *Design and add gates*
- e) *Fabricate shell and dry*
- f) *Dewax shell*
- g) *Pour casting*
- h) *Remove shell*
- i) *Remove gates*
- j) *Inspect (visual)*
- k) *Penetrant inspect (Rework, weld repair the rejects)*
- l) *Preliminary X-ray*
- m) *Solution anneal*
- n) *Straighten*
- o) *Age*
- p) *Second penetrant (approximately 10% fail)*
- q) *Final X-ray*
- r) *Final dimensional – approximately 3% rejected by foundry, an additional 2-5% by the customer)*

It was determined that the greatest contributor to excessive cost and time was the requirement for and the extent of rework. That rework usually requires further rework (over-grinding, weld repair, reheat treating, and re-straightening). The foundry estimated that 80% of the rework produced acceptable castings and 20% required secondary rework. The team decided that if this rework cycle was eliminated or drastically reduced, the wants from above should be obtainable.

The experiment focused on the rework cycle specifically to identify the factors that result in rework; an experiment was set up to test the sensitivity of the process to these factors. The factors (process steps at this point) impacting the investment casting process and their perceived sensitivity were discussed. They were ranked by team vote and are listed in Table 1.

**Table 1. Process Steps Ranked by Impact on the Investment Casting Process\***

| FACTOR           | TEST      |       |             | COST | TIME       |             | TEST TOTAL | COST & TIME TOTAL | OVERALL TOTAL |
|------------------|-----------|-------|-------------|------|------------|-------------|------------|-------------------|---------------|
|                  | PENETRANT | X-RAY | DIMENSIONAL |      | PRODUCTION | DEVELOPMENT |            |                   |               |
| Design           | 0         | 0     | 0           | 0    | 0          | 0           | 0          | 0                 | 0             |
| Wax              | 0         | 0     | 3           | 0    | 0          | 0           | 3          | 0                 | 3             |
| Gating           | 3         | 3     | 1           | 2    | 0          | 3           | 7          | 5                 | 12            |
| Shell and Drying | 1         | 1     | 3           | 1    | 2          | 2           | 5          | 5                 | 10            |
| Dewax            | 0         | 0     | 1           | 0    | 0          | 0           | 1          | 0                 | 1             |
| Fire Shell       | 0.5       | 0.5   | 2           | 0    | 0          | 0           | 3          | 0                 | 3             |
| Pour Casting     | 3         | 3     | 1           | 2    | 2          | 3           | 7          | 7                 | 14            |
| Remove Shell     | 1         | 0     | 0           | 1    | 1          | 1           | 1          | 3                 | 4             |
| Remove Gates     | 1         | 0     | 3           | 2    | 2          | 2           | 4          | 6                 | 10            |
| Weld Repair      | 2         | 1     | 3           | 3    | 3          | 3           | 6          | 9                 | 15            |
| Heat Treat       | 2         | 0     | 1           | 1    | 1          | 1           | 3          | 3                 | 6             |
| Straighten       | 2         | 0     | 3           | 3    | 3          | 3           | 5          | 9                 | 14            |
| Inspection       | 1         | 0.5   | 1           | 3    | 3          | 2           | 2.5        | 8                 | 10.5          |

0 DENOTES NO EFFECT, 1 WEAK EFFECT, 2 INTERMEDIATE AND 3 STRONG

\*Minutes from the Investment Casting Workshop, 2/20/91

From Table 1, the factors were ranked on sensitivity. They are:

| FACTOR        | TEST | COST & TIME | OVERALL |
|---------------|------|-------------|---------|
| POURING       | 7    | 7           | 14      |
| GATING        | 7    | 5           | 12      |
| WELD REPAIR   | 6    | 9           | 15      |
| STRAIGHTENING | 5    | 9           | 14      |
| SHELL AND DRY | 5    | 5           | 10      |

Weld repair was removed from the list concentrating on factors prior to it in the process flow in hopes of eliminating weld repair altogether. The list was further pared down to two factors, pouring and gating.

The team suggested and then voted on gating factors. The ranking of the gating factors was as follows:

|                          |    |
|--------------------------|----|
| <i>Operator factors</i>  | 20 |
| <i>Location of gates</i> | 15 |
| <i>Number of gates</i>   | 12 |
| <i>Fixturing of wax</i>  | 9  |
| <i>Area of gate</i>      | 8  |
| <i>Gate shape</i>        | 4  |
| <i>Fill orientation</i>  | 4  |
| <i>Head during pour</i>  | 1  |
| <i>Time in gating</i>    | 1  |
| <i>Table oil</i>         | 1  |

Additional factors that were identified but did not receive a vote were pads in die, hand vs. machine fabrication, wax properties, filtering techniques, storage conditions, wax pot temperature control, age of wax, and vents and risers.

The following final gating factors were agreed on by the team:

- *Wax assembler*
  - Two operators independently assembling the trees.
- *Fixture the patterns*
  - The patterns have a cantilevered section that drooped over time. Some patterns sat for two weeks unsupported, some sat in a fixture that supported the cantilever sections, and some were supported in water.
- *Number of gates*
- *Size of gates*
- *Location of gates*
  - Descriptions of these factors are in the Casting Design section of this report.

As with the gating factors, pouring factors were suggested and then voted on by the team. The ranking was as follows:

|                              |    |
|------------------------------|----|
| <i>Pour temperature</i>      | 12 |
| <i>Mold temperature</i>      | 10 |
| <i>Pour speed</i>            | 9  |
| <i>Mold orientation</i>      | 2  |
| <i>Vacuum or atmospheric</i> | 1  |
| <i>Time at temperature</i>   | 1  |
| <i>Crucible life</i>         | 1  |
| <i>De-gas</i>                | 1  |

Additional factors that were identified but did not receive a vote were lining material, alloy sequencing, head, hot top, and mold movement during solidification. The following final gating factors were agreed on by the team:

- *Pour operator*
  - Two different operators were used to independently manipulate the crucible during the pour.
- *Pour temperature*
  - Metal temperatures of 1500, 1600, and 1700 degrees centigrade were used.

- *Mold temperature*
  - *The molds were poured at 875, 1012, and 1150 degrees centigrade.*
- *Pour speeds*
  - *Pour duration of 3, 6, and 10 seconds from beginning to full mold were specified.*
- *Cooling profile*
  - *After the pour, the molds were subjected to forced air, still air, and slow air cooling by insulating the mold with KOA wool.*

The distribution of factors and the assigned casting serial numbers are listed in Table 2.

**Table 2. Experimental Design**

| Gating Factors  |             |             |           |                   | Pouring Factors |             |                |               |                 |     |
|-----------------|-------------|-------------|-----------|-------------------|-----------------|-------------|----------------|---------------|-----------------|-----|
| GATING OPERATOR | FIXTURE H2O | # OF GATES  | GATE SIZE | LOCATION OF GATES | POUR TEMP C     | MOLD TEMP C | POUR SPEED sec | POUR OPERATOR | COOLING PROFILE | S/N |
| Leif            | No Supports | FEWER       | SMALL     | OUTER             | 1500            | 875         | 10             | Sam           | Insulater w/KOA | 1   |
| Leif            | H2O         | FEWER       | LARGE     | OUTER             | 1500            | 875         | 10             | Mike          | Insulater w/KOA | 2   |
| Dave            | H2O         | FEWER       | LARGE     | INNER             | 1500            | 875         | 10             | Sam           | Fan Cooled      | 3   |
| Dave            | No Supports | FEWER       | SMALL     | INNER             | 1500            | 875         | 10             | Mike          | Fan Cooled      | 4   |
| Dave            | No Supports | MORE        | LARGE     | INNER             | 1500            | 875         | 3              | Sam           | Insulater w/KOA | 5   |
| Dave            | H2O         | MORE        | SMALL     | INNER             | 1500            | 875         | 3              | Mike          | Insulater w/KOA | 6   |
| Leif            | H2O         | MORE        | SMALL     | OUTER             | 1500            | 875         | 3              | Sam           | Fan Cooled      | 7   |
| Leif            | No Supports | MORE        | LARGE     | OUTER             | 1500            | 875         | 3              | Mike          | Fan Cooled      | 8   |
| Leif            | No Supports | MORE        | SMALL     | INNER             | 1500            | 1150        | 10             | Sam           | Insulater w/KOA | 9   |
| Leif            | H2O         | MORE        | LARGE     | INNER             | 1500            | 1150        | 10             | Mike          | Insulater w/KOA | 10  |
| Dave            | H2O         | MORE        | LARGE     | OUTER             | 1500            | 1150        | 10             | Sam           | Fan Cooled      | 11  |
| Dave            | No Supports | MORE        | SMALL     | OUTER             | 1500            | 1150        | 10             | Mike          | Fan Cooled      | 12  |
| Dave            | No Supports | FEWER       | LARGE     | OUTER             | 1500            | 1150        | 3              | Sam           | Insulater w/KOA | 13  |
| Dave            | H2O         | FEWER       | SMALL     | OUTER             | 1500            | 1150        | 3              | Mike          | Insulater w/KOA | 14  |
| Leif            | H2O         | FEWER       | SMALL     | INNER             | 1500            | 1150        | 3              | Sam           | Fan Cooled      | 15  |
| Leif            | No Supports | FEWER       | LARGE     | INNER             | 1500            | 1150        | 3              | Mike          | Fan Cooled      | 16  |
| Dave            | H2O         | MORE        | SMALL     | OUTER             | 1700            | 875         | 10             | Sam           | Insulater w/KOA | 17  |
| Dave            | No Supports | MORE        | LARGE     | OUTER             | 1700            | 875         | 10             | Mike          | Insulater w/KOA | 18  |
| Leif            | No Supports | MORE        | LARGE     | INNER             | 1700            | 875         | 10             | Sam           | Fan Cooled      | 19  |
| Leif            | H2O         | MORE        | SMALL     | INNER             | 1700            | 875         | 10             | Mike          | Fan Cooled      | 20  |
| Leif            | H2O         | FEWER       | LARGE     | INNER             | 1700            | 875         | 3              | Sam           | Insulater w/KOA | 21  |
| Leif            | No Supports | FEWER       | SMALL     | INNER             | 1700            | 875         | 3              | Mike          | Insulater w/KOA | 22  |
| Dave            | No Supports | FEWER       | SMALL     | OUTER             | 1700            | 875         | 3              | Sam           | Fan Cooled      | 23  |
| Dave            | H2O         | FEWER       | LARGE     | OUTER             | 1700            | 875         | 3              | Mike          | Fan Cooled      | 24  |
| Dave            | H2O         | FEWER       | SMALL     | INNER             | 1700            | 1150        | 10             | Sam           | Insulater w/KOA | 25  |
| Dave            | No Supports | FEWER       | LARGE     | INNER             | 1700            | 1150        | 10             | Mike          | Insulater w/KOA | 26  |
| Leif            | No Supports | FEWER       | LARGE     | OUTER             | 1700            | 1150        | 10             | Sam           | Fan Cooled      | 27  |
| Leif            | H2O         | FEWER       | SMALL     | OUTER             | 1700            | 1150        | 10             | Mike          | Fan Cooled      | 28  |
| Leif            | H2O         | MORE        | LARGE     | OUTER             | 1700            | 1150        | 3              | Sam           | Insulater w/KOA | 29  |
| Leif            | No Supports | MORE        | SMALL     | OUTER             | 1700            | 1150        | 3              | Mike          | Insulater w/KOA | 30  |
| Dave            | No Supports | MORE        | SMALL     | INNER             | 1700            | 1150        | 3              | Sam           | Fan Cooled      | 31  |
| Dave            | H2O         | MORE        | LARGE     | INNER             | 1700            | 1150        | 3              | Mike          | Fan Cooled      | 32  |
| Leif            | Fixture     | As Produced | MEDIUM    | As Produced       | 1600            | 1012        | 6              | Mike          | Still Air       | 33  |
| Leif            | Fixture     | As Produced | MEDIUM    | As Produced       | 1600            | 1012        | 6              | Mike          | Still Air       | 34  |
| Leif            | Fixture     | As Produced | MEDIUM    | As Produced       | 1600            | 1012        | 6              | Mike          | Still Air       | 35  |
| Leif            | Fixture     | As Produced | MEDIUM    | As Produced       | 1600            | 1012        | 6              | Mike          | Still Air       | 36  |

## Responses

The responses were taken from the original list of major process steps. They are X-ray, penetrant, and dimensional inspection. Dimensional inspection would take place on the wax pattern directly after injection, just before wax assembly, just after assembly, and as a casting after gate removal. X-ray was performed on the castings after gate removal.

## Casting Design

In brainstorming sessions the team came up with the ideal shape for the casting to be studied. We wanted the casting to have the same difficult-to-cast features as production castings. These include thin walls (0.090 inches), thick-to-thin transitions, cantilevered sections, pockets, holes, curved surfaces, "T" sections, and a total enclosed volume of approximately 1 cubic foot. Rather than build a test casting, we opted to modify the wax injection tooling of an obsolete production casting. A former production casting brings along some history of the gating from its production life. Out of several obsolete castings, the base plate was chosen.

This was an extremely complicated casting in its production and has all of the challenging features we wanted. The connector frame defined in zone B-4 by the 42, 46, 61, and 65 dimensions (Figure 1) was removed from the injection tool because it is too straightening sensitive. The cantilevered section above datum point A3 was modified by filling in the recessed area (Figure 2). This made for a greater surface area to inspect and more mass for the cantilever effect. The stronglink pad's thickness in view DD was increased from 0.06 inches (1.5 mm) to 0.25 inches to provide more of a thick-to-thin transition (Figure 3).

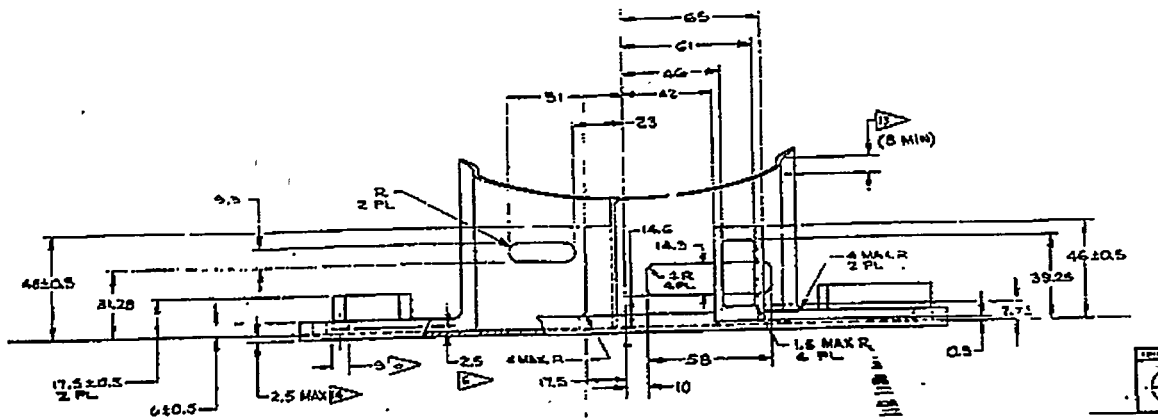
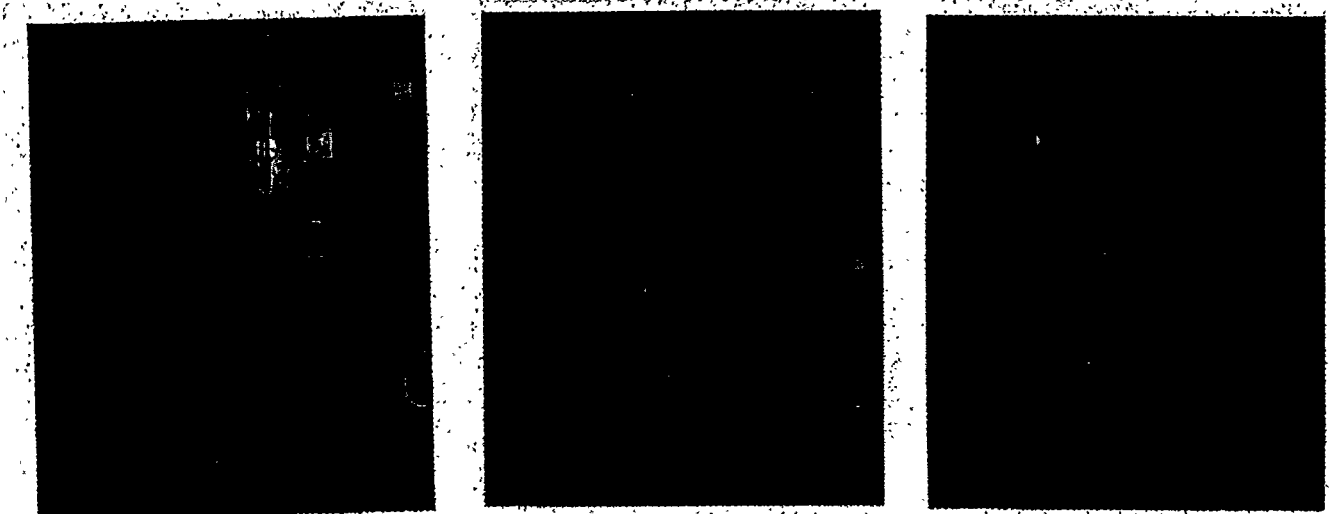


Figure 1. Casting Drawing Showing the Frame

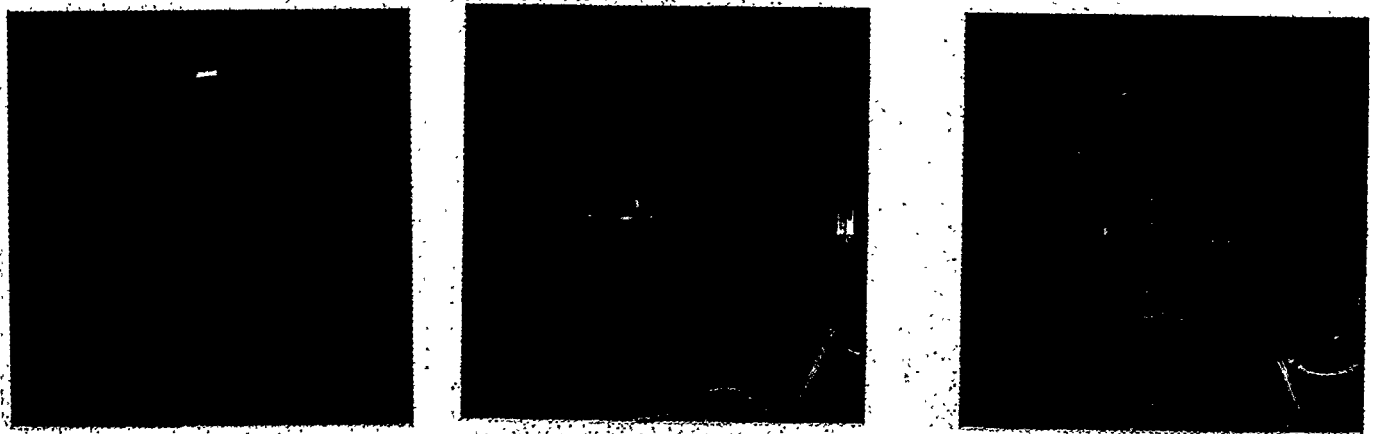


**Number of Gates and Gate Location**

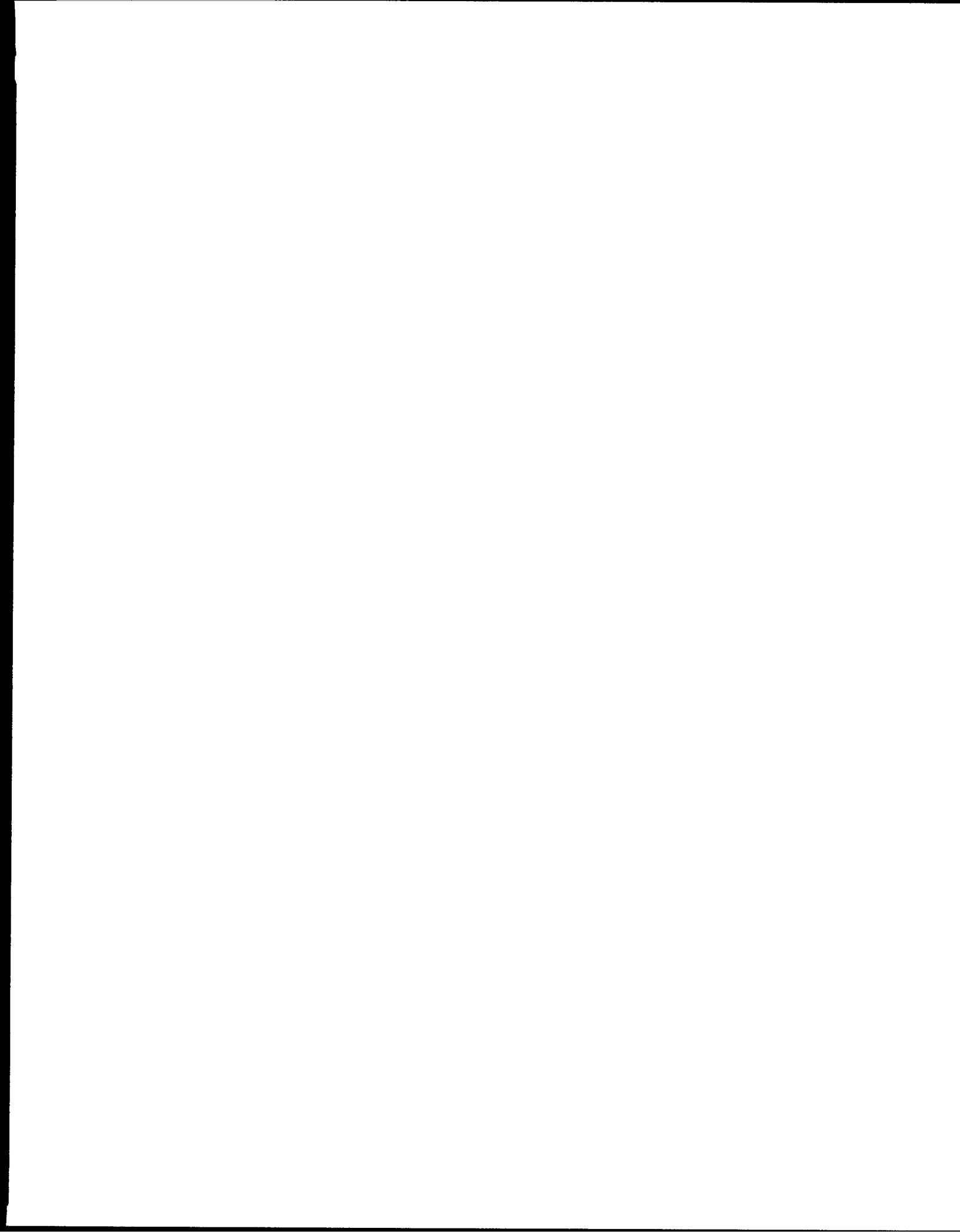
The null gating configuration is based on the gating history while it was in production. Six gates were added to the top of the null gating scheme for the more gating scheme. All of the gates on the top of the null scheme were removed along with nine on the lower surface for the fewer gating scheme. See Figures 4 through 7.

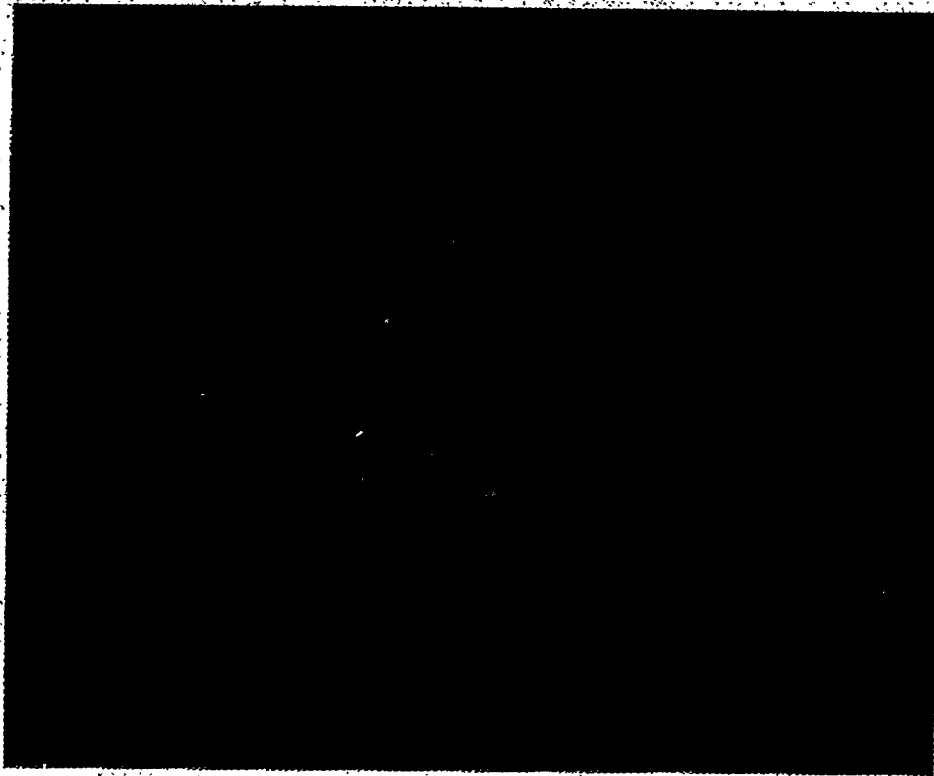


**Figure 4. Best Practice More Number of Gates Configuration**

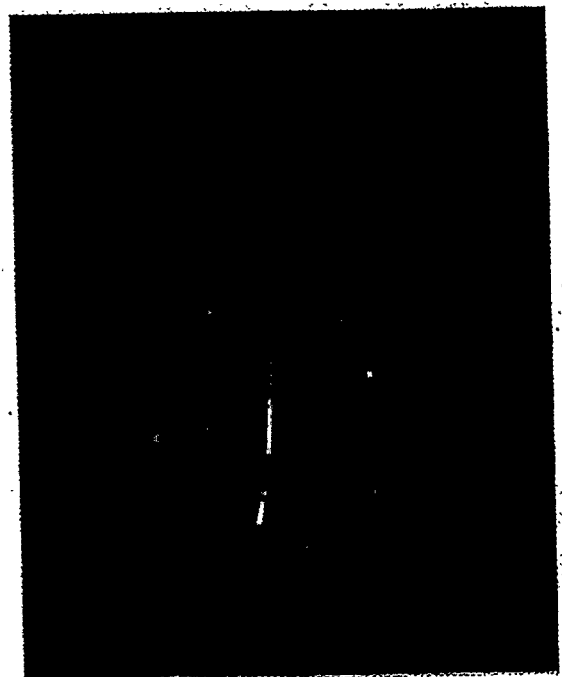
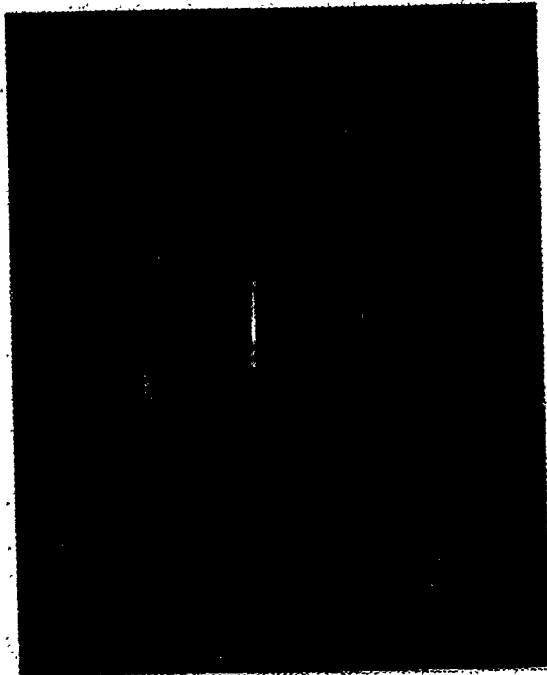


**Figure 5. Null Gating Closely Resembling That of Production Gating**

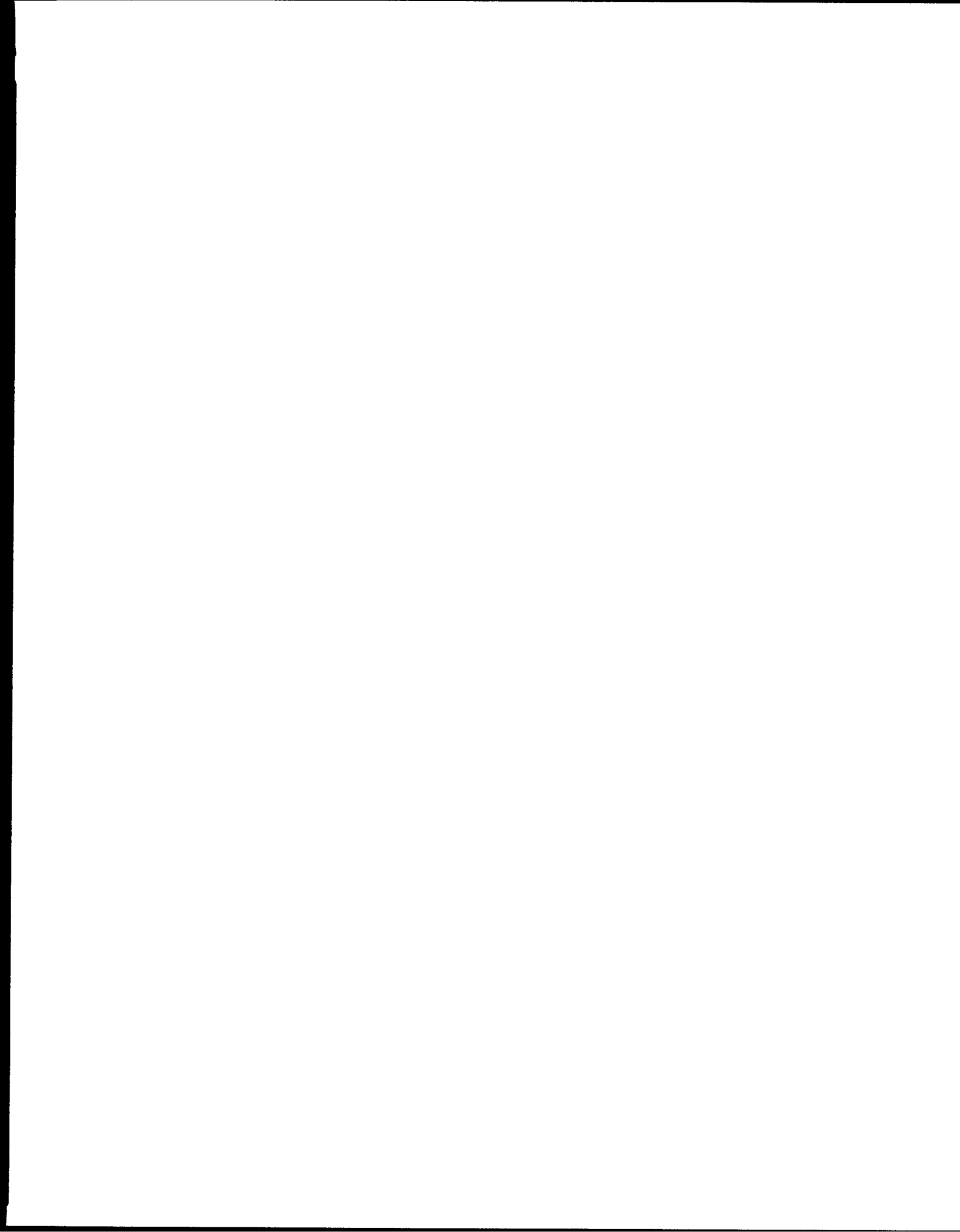




**Figure 6. Fewer Gating Configuration. No Gates on the Opposite Side**



**Figure 7. Partially Assembled More Gates Configuration With Runners**



The gate location parameter affects only those gates on the top outside perimeter. These gates are shifted outboard as far as they can go for the *outer* configuration, inboard as far as they can go for the inner configuration and in the middle for the null gating configuration. In the team's opinion the outside condition should produce the best results due to reduced turbulence and improved cooling.

### Gate Size

Gate sizes were based on what was used on the production castings and what was readily available. Table 3 lists the sizes of the gates used in all three configurations. The team's initial decision was to use the production size gates for the null configuration and scale up and down 25% of the null area for the plus and minus gate size parameter. Readily available wax sizes that came closest to the prescribed areas were used .

**Table 3. Gate Sizes and Areas**

Gate sizes for the Null, Small and Large configuration (inches)

| NULL      | 25% OFF NULL | ACTUAL     | 25% ADDED TO NULL | ACTUAL     |
|-----------|--------------|------------|-------------------|------------|
| AREA      | AREA         | AREA       | AREA              | AREA       |
| 1/4 x 3/4 | 0.1875       | 3/16 x 3/4 | 0.234375          | 5/16 x 3/4 |
|           | 0.140625     | 0.1406     |                   | 0.2344     |
| 3/8 x 3/4 | 0.2813       | 5/16 x 3/4 | 0.351625          | 1/2 x 3/4  |
|           | 0.210975     | 0.2344     |                   | 0.375      |
| 3/8 x 1/2 | 0.1875       | 5/16 x 1/2 | 0.234375          | 1/2 x 1/2  |
|           | 0.140625     | 0.1563     |                   | 0.25       |
| 1/2 x 1   | 0.5          | 3/8 x 1    | 0.625             | 5/8 x 1    |
|           | 0.375        | 0.375      |                   | 0.625      |
| 1/2 x 3/4 | 0.375        | 1/2 x 5/8  | 0.46875           | 1/2 x 7/8  |
|           | 0.28125      | 0.3125     |                   | 0.4375     |
| 1/2 dia   | 0.1963       | 7/16 dia   | 0.245375          | 9/16 dia   |
|           | 0.147225     | 0.1503     |                   | 0.2485     |
| 5/8 dia   | 0.306        | 9/16 dia   | 0.3825            | 11/16 dia  |
|           | 0.2295       | 0.2485     |                   | 0.3712     |

Figures 8 and 9 and Table 4 illustrate where and what size of gates were used on the more gate configuration. In the null configurations, gates 23-25 and 27-30 were omitted. On the fewer gates configuration, all of the gates on the top and gates 4, 6, 9, 13, 15-17, 19, and 20 on the bottom were omitted. See also Figures 5 and 6.

### Dimensional Results

Dimensional responses were measured at specific areas of the casting. Referring to Figure 10, the areas are Surface A in red, left and right cantilever pads in green, bottom of the "T" in brown, right and left top of the "T" in purple, and the 115.06 edge in light blue.

To simplify the measuring process, dimensional data was recorded as flatness data. It is assumed that if the process will yield the flat surfaces consistently then the wax injection tools can be tweaked to move the surface to the nominal location.

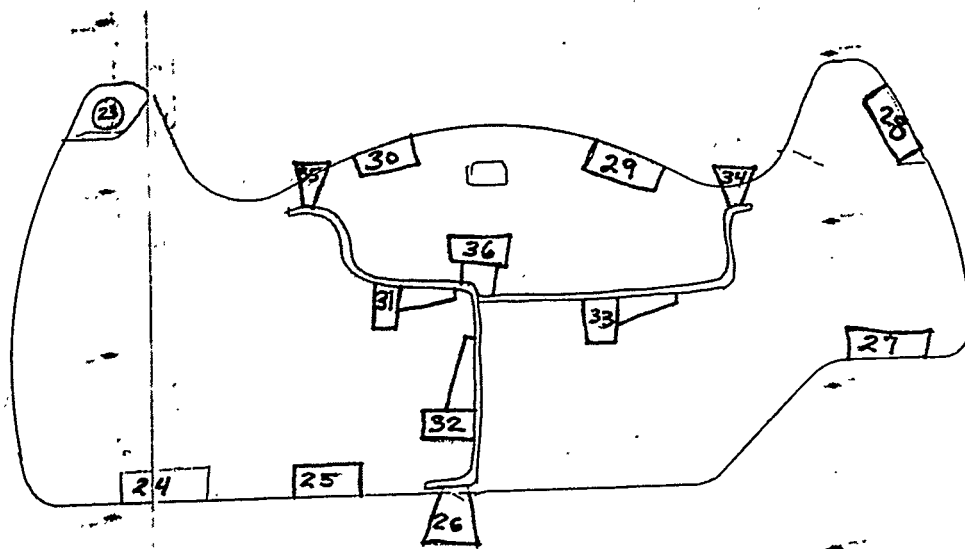


Figure 8. Gate Pad Labels for the Top of the Casting

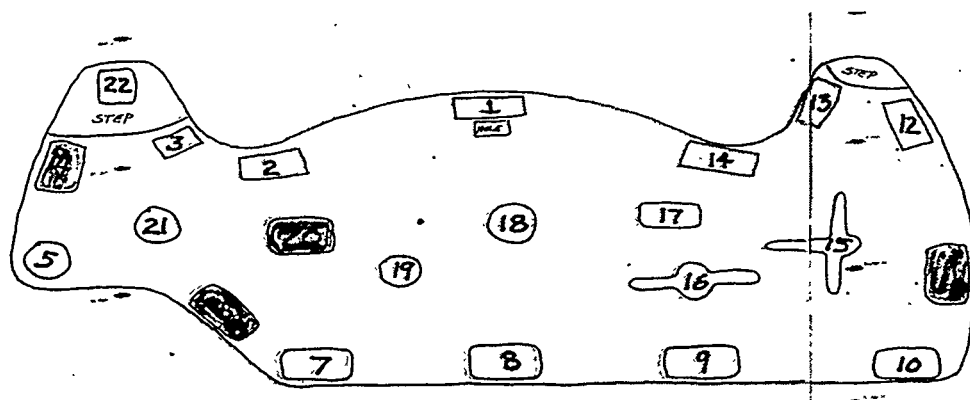
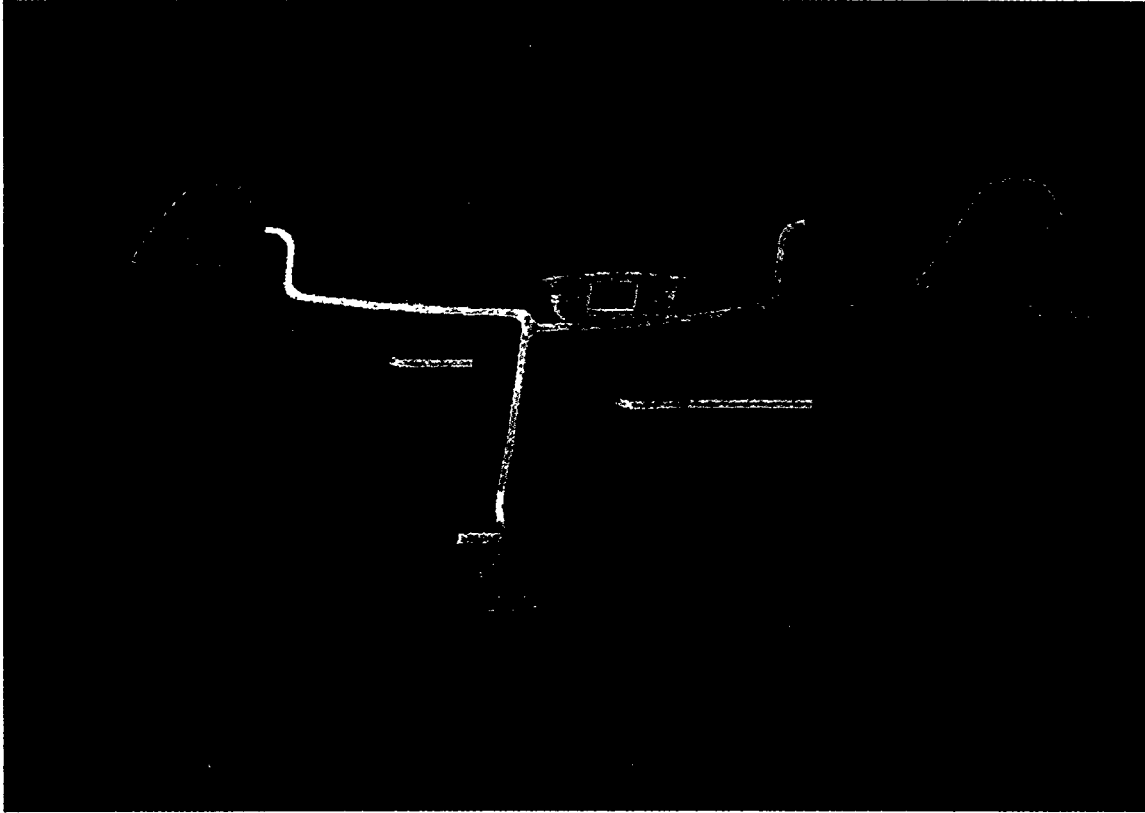


Figure 9. Gate Pad Labels for the Bottom of the Casting

Table 4. Gate Size and Placement for the More Number of Gates Configuration Gate Map

|        | Gate Number   | Null Size  | Small size | Large Size |
|--------|---------------|------------|------------|------------|
| Bottom | Remainder     | 1/4 x 3/4  | 3/16 x 3/4 | 5/16 x 3/4 |
|        | 4, 6, 11, 20  | 3/8 x 3/4  | 5/16 x 3/4 | 1/2 x 3/4  |
|        | 5, 18, 19, 21 | 1/2 x 3/4  | 1/2 x 5/8  | 1/2 x 7/8  |
|        | 15, 16*       | 1/2 dia    | 7/16 dia   | 9/16 dia   |
|        |               | 1/2 dia    | 7/16 dia   | 9/16 dia   |
| Top    | Remainder     | 1/4 x 3/4  | 3/16 x 3/4 | 5/16 x 3/4 |
|        |               | 3/8 x 3/4  | 5/16 x 3/4 | 1/2 x 3/4  |
|        |               | 1/2 x 3/4  | 1/2 x 5/8  | 1/2 x 7/8  |
|        | 23            | 1/2 dia    | 7/16 dia   | 9/16 dia   |
|        | 36            | 1/2 x 1/2  | 1/2 x 1/2  | 1/2 x 1/2  |
|        | 31, 32, 33*   | 1/2 dia    | 7/16 dia   | 9/16 dia   |
|        | 34, 35        | 3/16 x 3/4 | 1/8 x 3/4  | 1/4 x 3/4  |

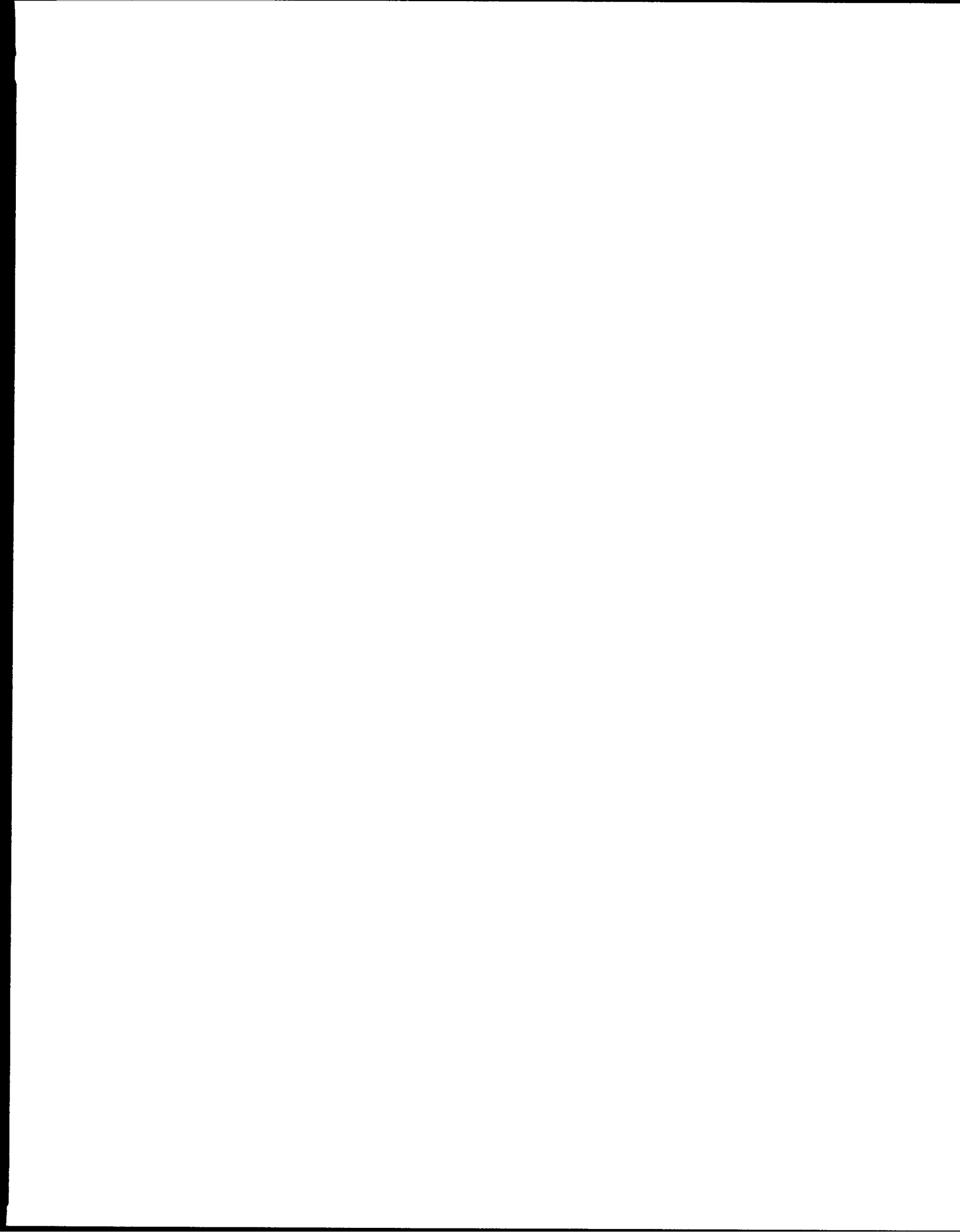
\* Irregular, different diameters same leg size



**Figure 10. Computer Model of the Casting Showing the Inspection Areas**

To capture the effects of the process on the dimensions, the “parts” were measured at four stages in the production process. The wax pattern was first measured within 2 hours of being injected. This serves as a baseline for follow-on measurements. The second measurement of the wax pattern was after 2 weeks of storage. In a large production foundry, it is not an unlikely scenario for patterns to sit in storage for weeks before they begin the gating process. If the wax support factor is sensitive, this is where it will show up. The third measurement of the wax pattern was after assembly of the gates and runners. It was suggested by a team member that the gates and runners place the pattern in a stressed state and deform it before it is shelled. The last measurement of the casting is after gate removal and prior to straightening. Since this is a casting experiment, it was decided to skip the straightening step altogether. It was agreed that straightening, if done properly, can fix even a badly warped casting. If this step can be reduced or eliminated, our original list of wants is more obtainable.

The dimensional responses are tabulated in Appendix A. The dimensional response for each process variable at each location was plotted against the four process steps. The charts are in Appendix A.



### *Process Variable 1, Wax Assemblers*

Two different wax assemblers were used to assemble the pattern, runners, gates, and pour cup. Differences in their style were noticeable. One worked meticulously on bonding the wax together and dripping a fillet of wax around the joints. The other worked faster and was able to build the assemblies faster. The dimensional response differences as graphed on Appendix A, page 25, should be discernible at the GATE level and beyond. Prior to this, WAX and WAX1 are essentially the same with regard to the wax assemblers. In some measured areas, the D castings have a greater variability than the (L) castings although the amount may be smaller than measurement noise.

### *Process Variable 2, Water Support vs. No Support*

The patterns are measured immediately after they came from the injection tool (WAX). Half were stored base down on a flat surface; the others were floating in water. After two weeks the patterns were measured again (WAX1). Cold flow or creep should be most noticeable in the cantilever areas on the pattern. The graph on Appendix A, page 27, shows little difference between water and unsupported patterns.

### *Process Variable 3, Fewer vs. More Gates*

The effects of this process variable show up on Appendix A, page 29. The "Fewer Gates" processed parts have more variability than the "More Gates" parts. It also affects the X-ray responses.

### *Process Variable 4, Small vs. Large Gates*

On Appendix A, page 31, the dimensional responses to the size of gates are very close to the same.

### *Process Variable 5, Outer vs. Inner Placement of Gates*

Here the gates along the perimeter of the pattern were displaced toward the inside on half of the assemblies. The expected result was to have the outer gate placement transfer more force to the casting from the contracting gates and runners during cooling. Differences between the inner and outer were not found.

### *Process Variable 6, 1500 °C vs. 1700 °C Pour Temperatures*

On Appendix A, page 35, the dimensional responses to the temperature of the pours are very close to the same.

### *Process Variable 7, 875°C vs. 1150°C Mold Temperatures*

There seems to be a small shift upwards in the variability of the castings processed at 1150°C.

### *Process Variable 8, Pour Speed 10 Seconds vs. 3 Seconds*

On Appendix A, page 39, the dimensional responses to the pour speeds are very close to the same.

### *Process Variable 9, Pour Operators*

On Appendix A, page 41, the dimensional responses to the pour operators are very close to the same.

### *Process Variable 10, Mold Cooling Profiles*

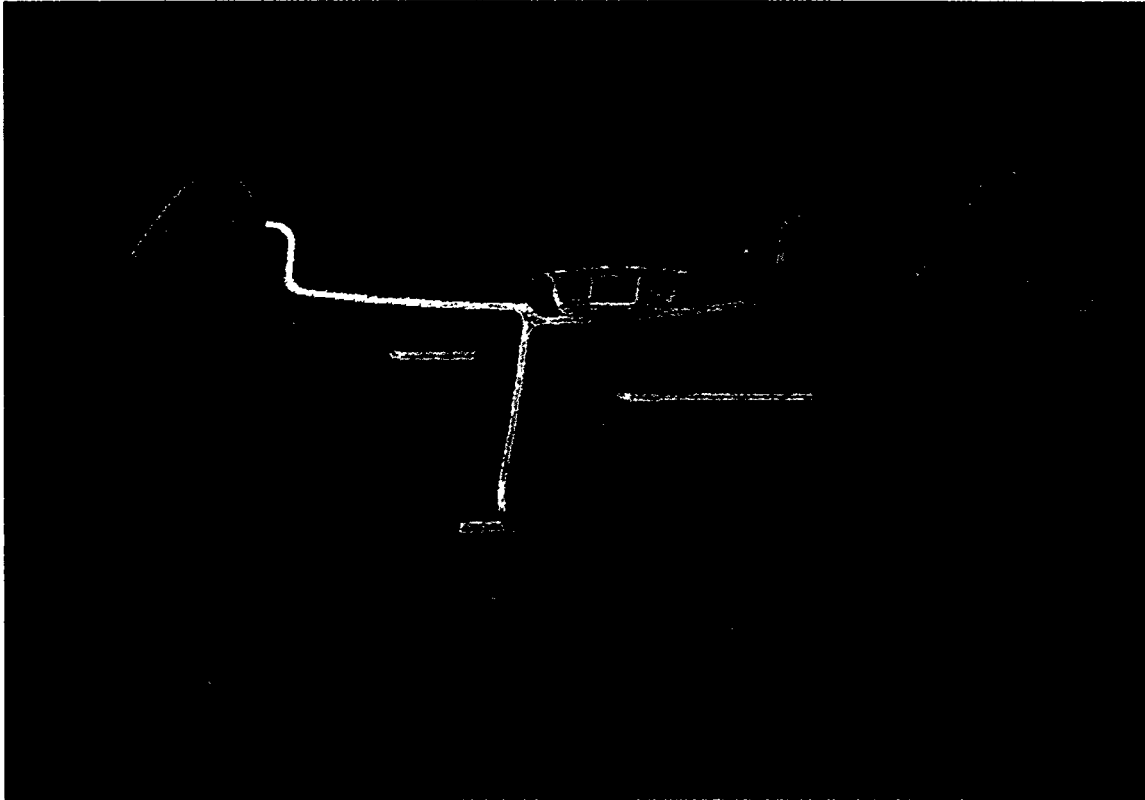
On Appendix A, page 43, the dimensional responses to the insulated vs. fan cooled castings are very close to the same.

## **Radiographic Results**

The castings were radiographically inspected. Defects were categorized into six locations, plus type and severity of defect. Referring to Figure 11, the areas of radiographic inspection are Surface A in red, left and right cantilever pads in green, bottom of the “T” in brown, right and left top of the “T” in purple, and the rim in light blue.

The raw radiographic inspection data is included in Appendix B. Radiographic defects were grouped into three categories in order of severity. Type A failure modes, the least desirable, contains Non-Fills, Through Hole, Cracks, and Cold Shuts. Type B failure modes contain Dendritic Shrinkage, Gas Holes, Filament Shrinkage, and Shell Breaks. Type C failure modes contain Foreign Material, Surface Visual, and Surface Depressions. Table 5 shows the results as optimum settings for each factor for each of the three types of failures.

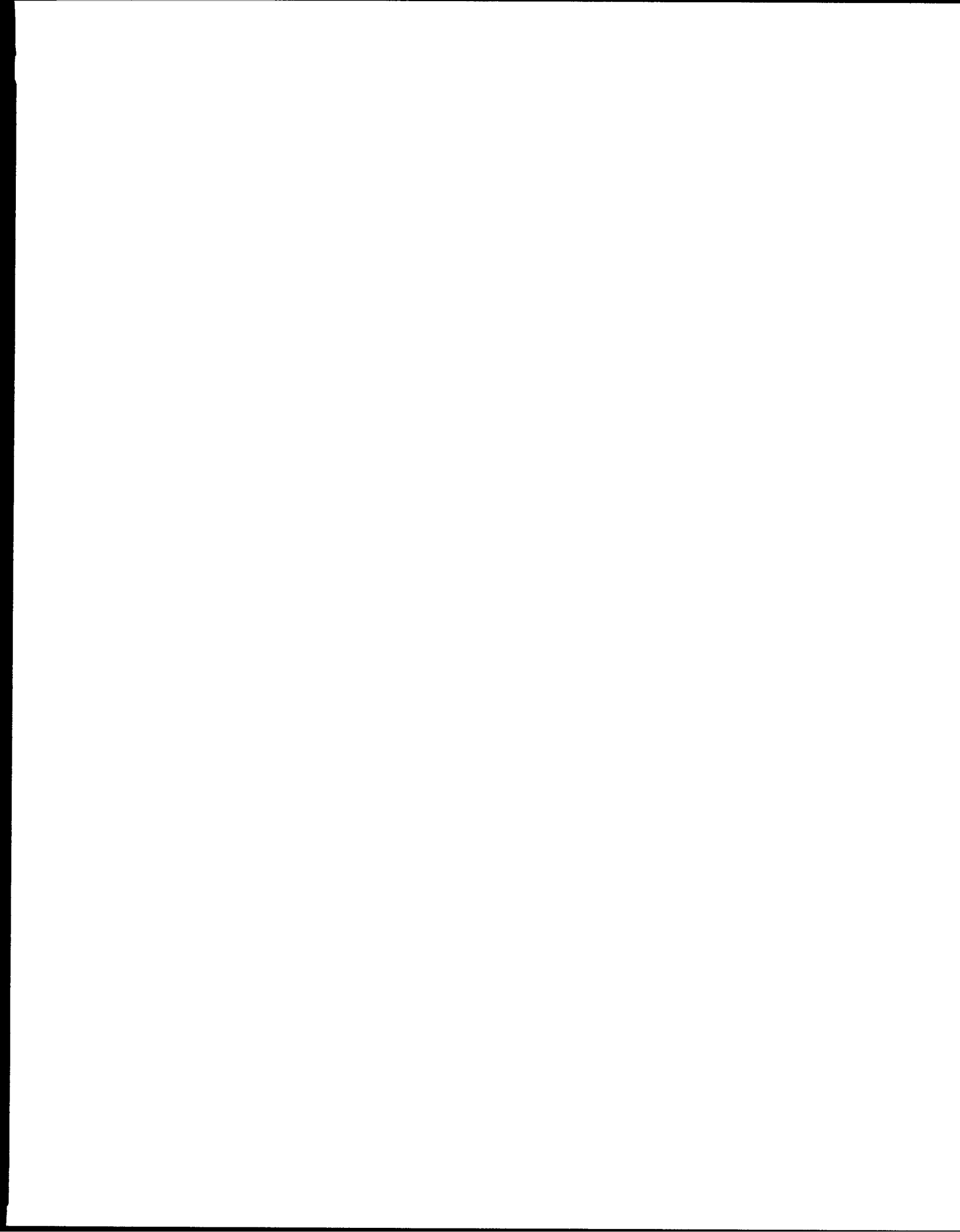
Conflicts between treatments for the three types of failures can be handled by using the factor settings that minimize the least desirable types of failure, in this case type A. The number of gate settings for type A is contrary to conventional wisdom. Based on location of defects, the number of gates can be set to the type B setting. See Appendix C, “Statistical Analysis of Casting Experiment.” Further experimentation can resolve these inconsistencies.



**Figure 11. Computer Model of the Casting Showing the Inspection Areas (Second View)**

**Table 5. Suggested Factor Settings to Optimize X-ray Responses (See Appendix B)**

| Factors       | Type A        | Type B        | Type C    |
|---------------|---------------|---------------|-----------|
| Gate Location | Inner Rim     | Inner Rim     | Inner Rim |
| Fixture       | Not Supported | Not Supported | Water     |
| Pour Temp     | 1700°C        | 1700°C        | 1500°C    |
| Mold Temp     | 875°C         | 1150°C        | 875°C     |
| Pour Speed    | 3 Seconds     | 3 Seconds     | 3 Seconds |
| Cooling       | Insulated     | Insulated     | Fan       |
| Gate Operator | ...           | ...           | ...       |
| Pour Operator | ...           | ...           | ...       |
| No. of Gates  | Fewer         | More          | More      |
| Size of Gates | ...           | ...           | ...       |



## Conclusions

The following factors did not have an impact on either the dimensional or radiographic responses:

- Pour Operators and the Size of Gates

The following factors impacted both the dimensional and radiographic responses:

- Fewer vs. More Gates
  - More gates tend to reduce dimensional variability and radiographic failures. This could be due to a number of reasons such as faster fill of the mold, shorter flow distances in the mold, slower cooling, and a stiffer structure to resist warping.
- Mold Temperature
  - The lower temperature tended to reduce dimensional variability and radiographic failures.

The following factors impacted the radiographic responses:

- Gate Location
  - The inner location produces less radiographic failures. Such things as less turbulence and shorter flow distances in the mold could explain this result.
- Pour Temperature
  - The higher pour temperature produced better results.
- Pour Speed
  - The faster the pour, the better the results. There is probably a trade-off to this in that turbulence will adversely affect the results at even higher pour speeds.
- Cooling Profile
  - Slower cooling produced less radiographic problems. The insulation allows for controlled solidification from the center to the exterior gates.
- Fixture
  - The waxes that were stored on a flat surface as opposed to those floating in water had less type A and B problems. This factor was envisioned to cause a dimensional response but it did not. Since the waxes are essentially the same in that they are dimensionally the same, there is no logical explanation why it affected the radiographic responses.

The following factors impacted the dimensional responses:

- Gate Assemblers
  - Slightly less dimensional variability was found with (L). This result may be an aberration in that (L) generally produces assemblies faster but not as consistent as (D). The results are contradictory to the expected speed vs. consistency comparison.

## ACCOMPLISHMENTS

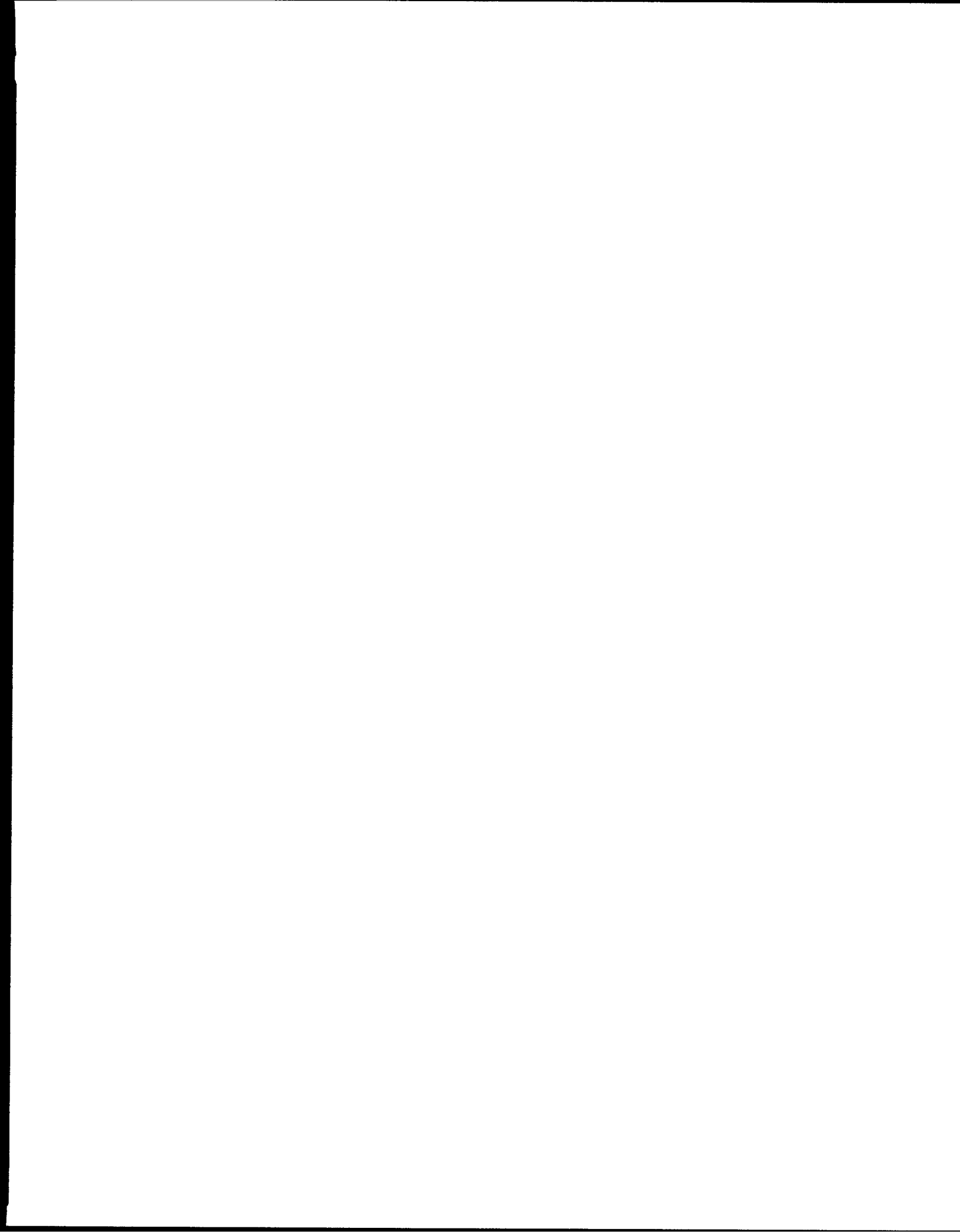
Photographs of the final castings are shown in Appendix D. In reference to the process variables addressed in this study, the optimum processing is as follows:

- Gate location, inner rim
- No fixture
- Pour temperature at 1700°C
- Fast pour
- Insulate the mold for a slow cool
- Larger number of gates

Two of the parameters seem to go against conventional wisdom. Our experiment indicates to reduce “type A” X-ray failure modes, the mold temperatures should be set at the lower temperatures and fewer gates should be used. A verification study could be performed to further study the interaction of these process variables.

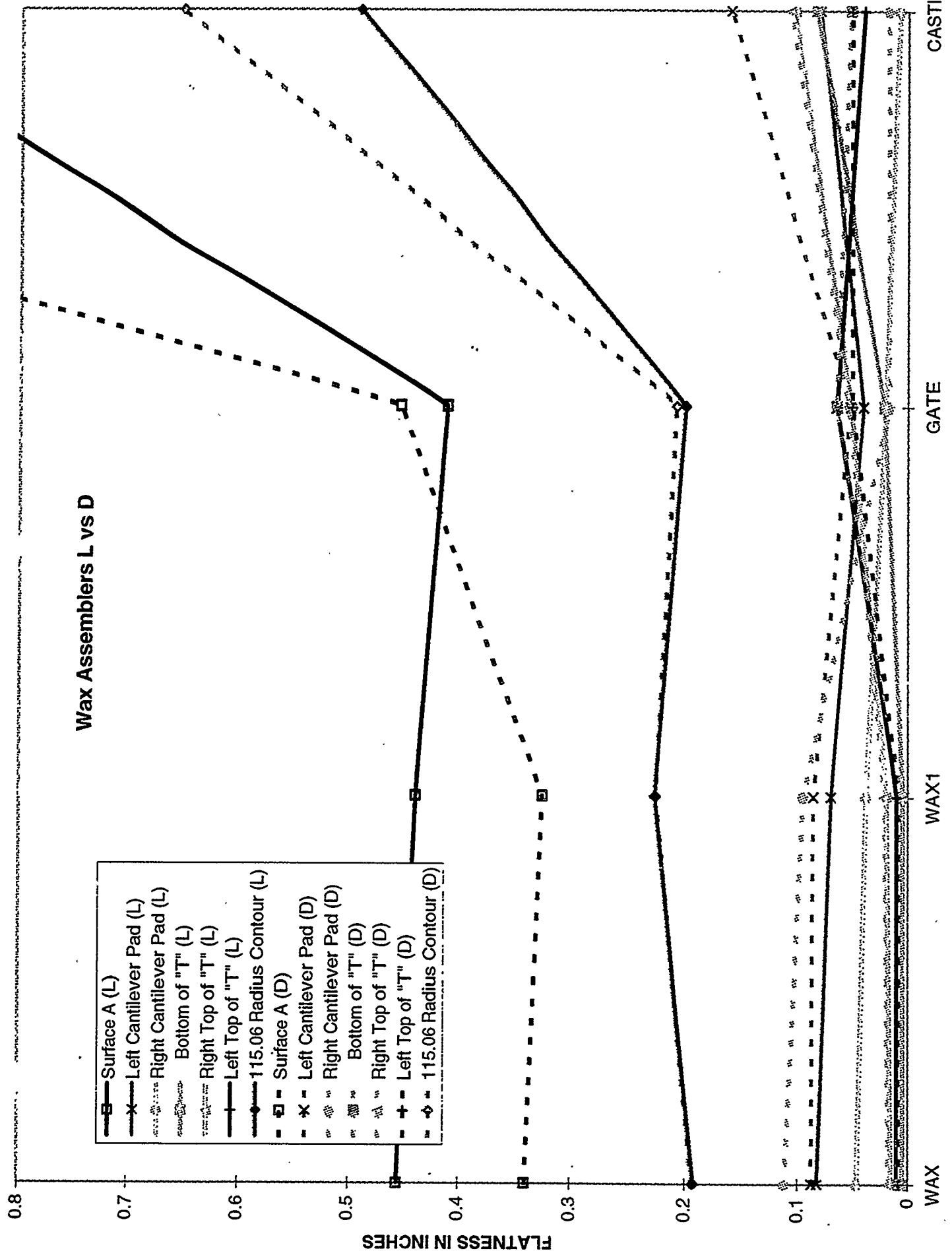
## **APPENDIX A**

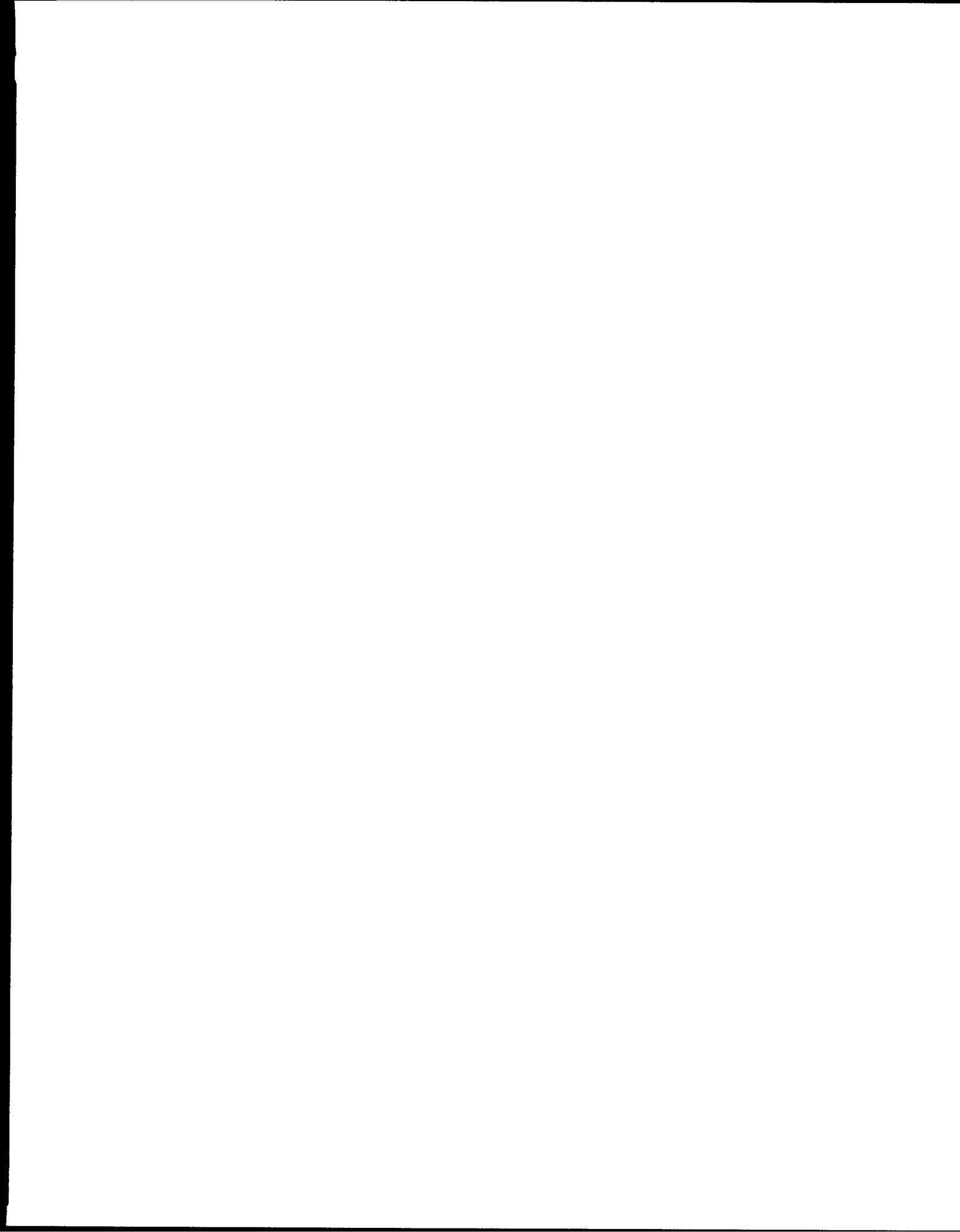
### **Radiographic Data**

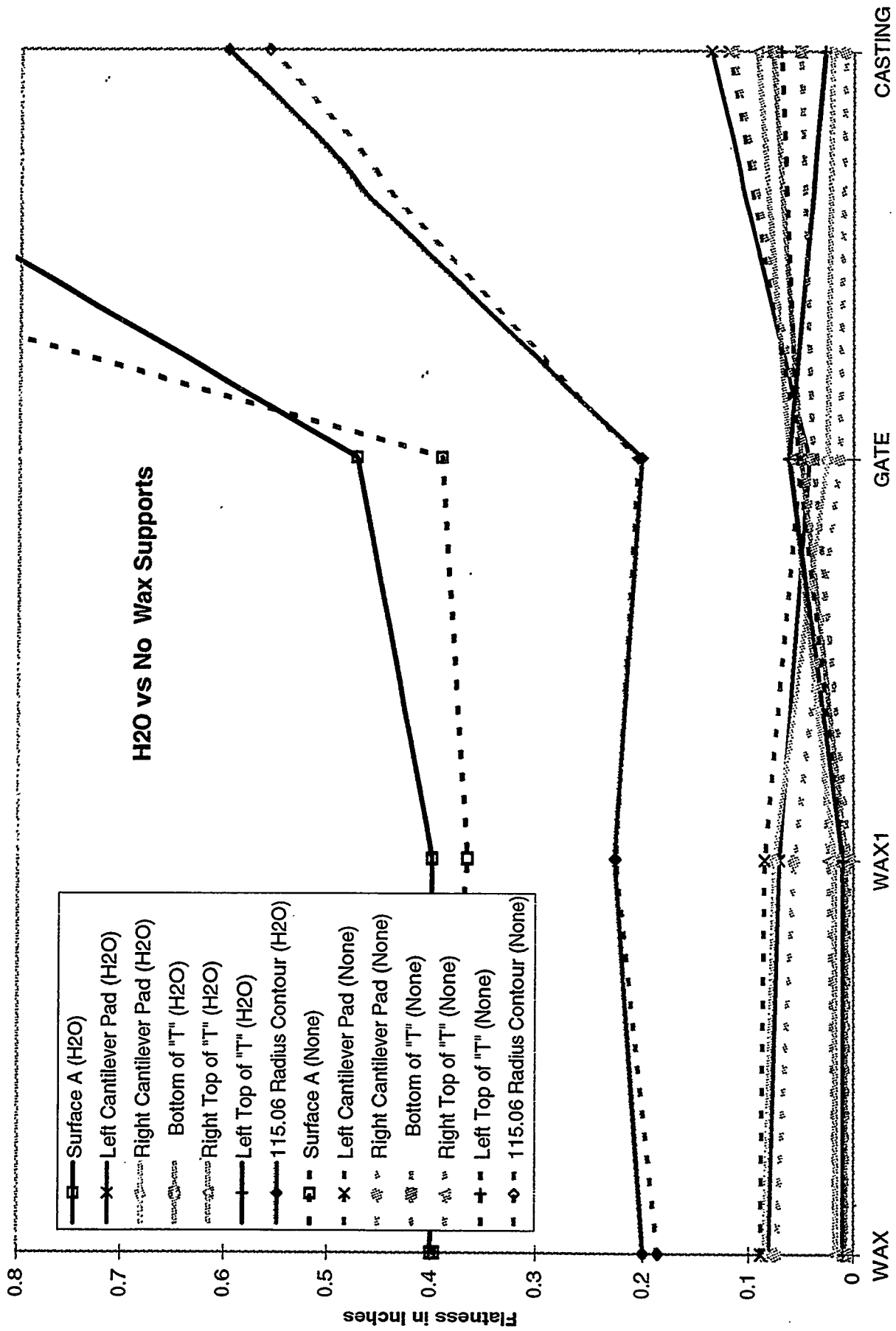


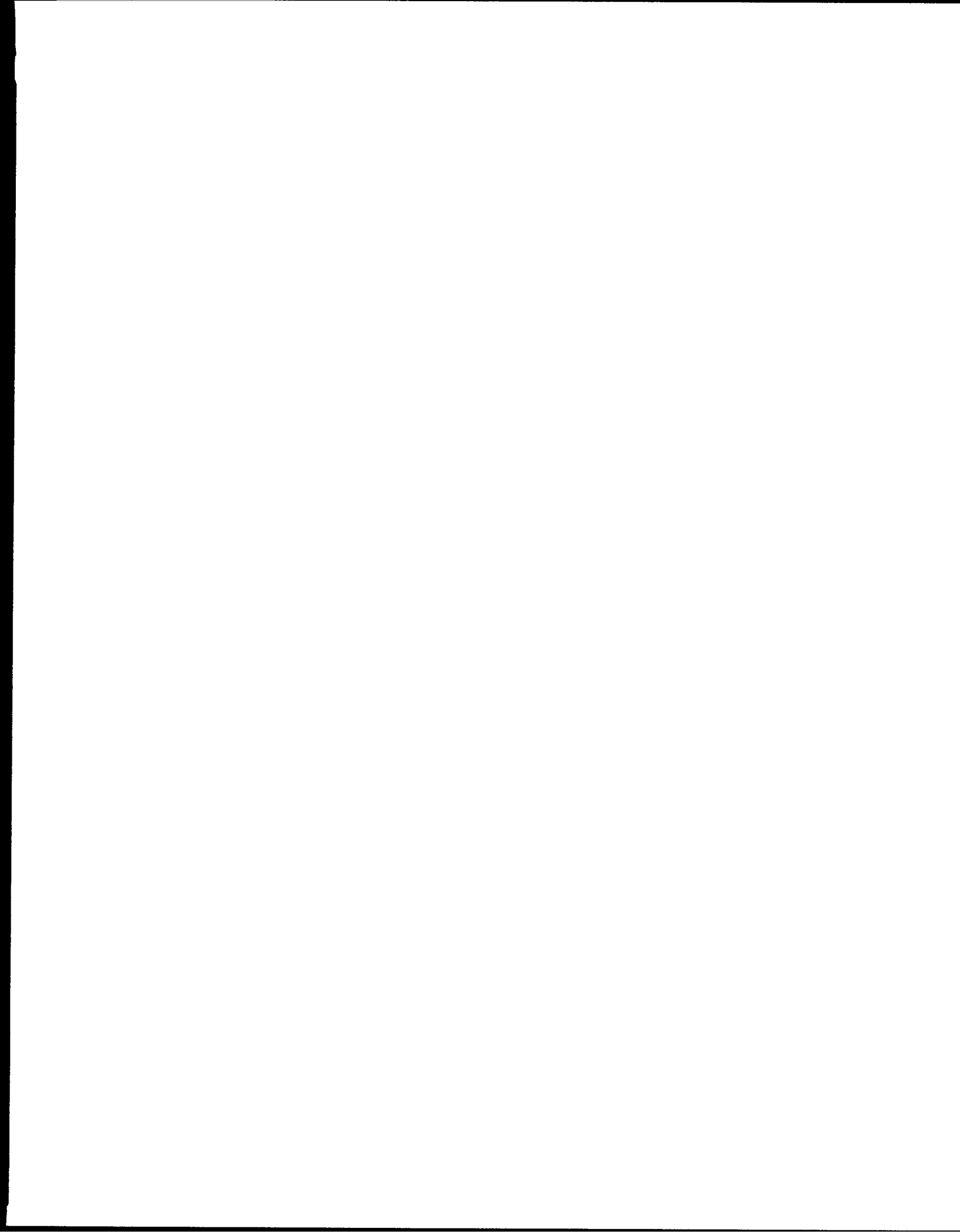
# Wax Assemblers L vs D

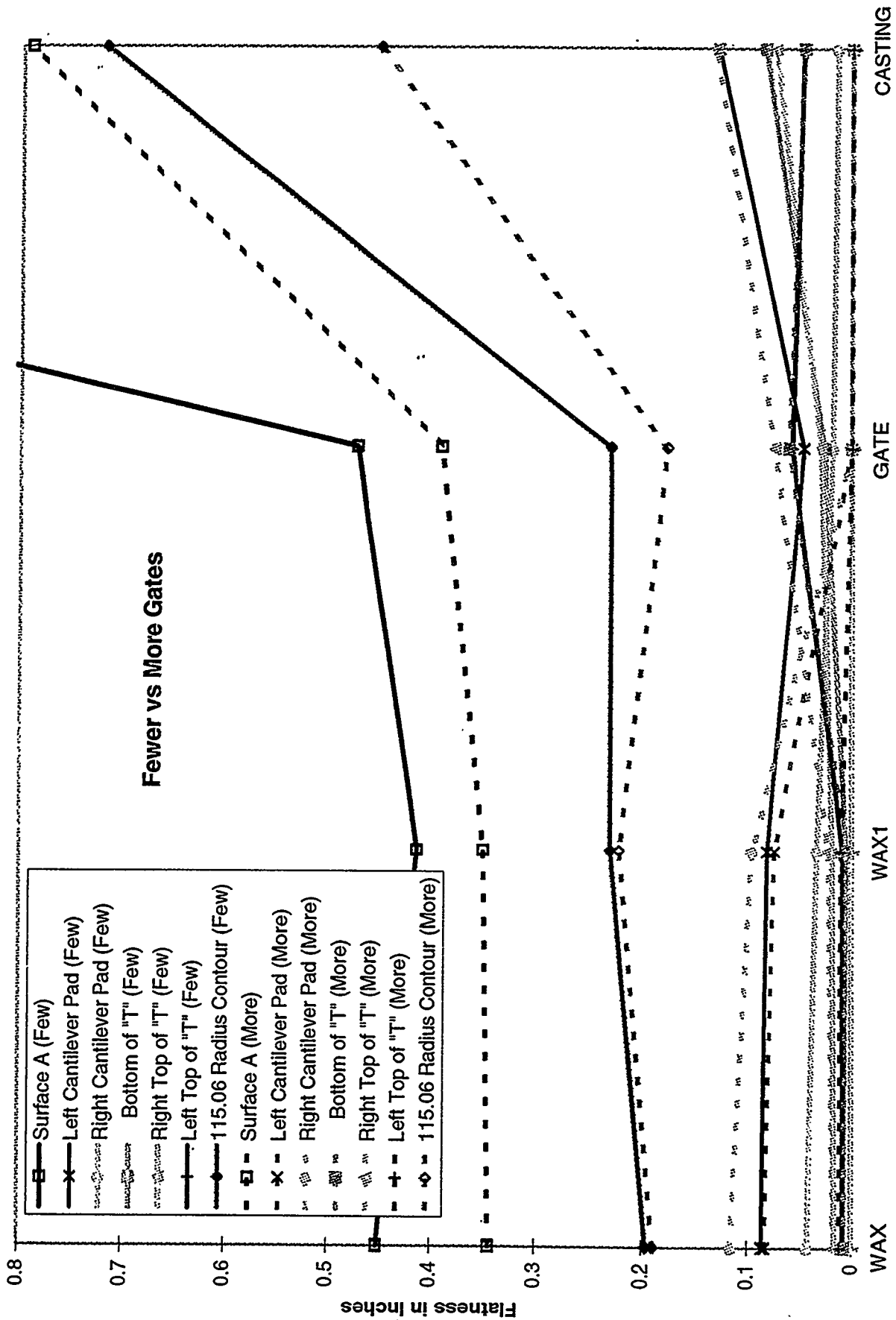
- Surface A (L)
- x— Left Cantilever Pad (L)
- Right Cantilever Pad (L)
- +— Bottom of "T" (L)
- o— Right Top of "T" (L)
- ◇— Left Top of "T" (L)
- ◆— 115.06 Radius Contour (L)
- Surface A (D)
- x— Left Cantilever Pad (D)
- Right Cantilever Pad (D)
- +— Bottom of "T" (D)
- o— Right Top of "T" (D)
- ◇— Left Top of "T" (D)
- ◆— 115.06 Radius Contour (D)

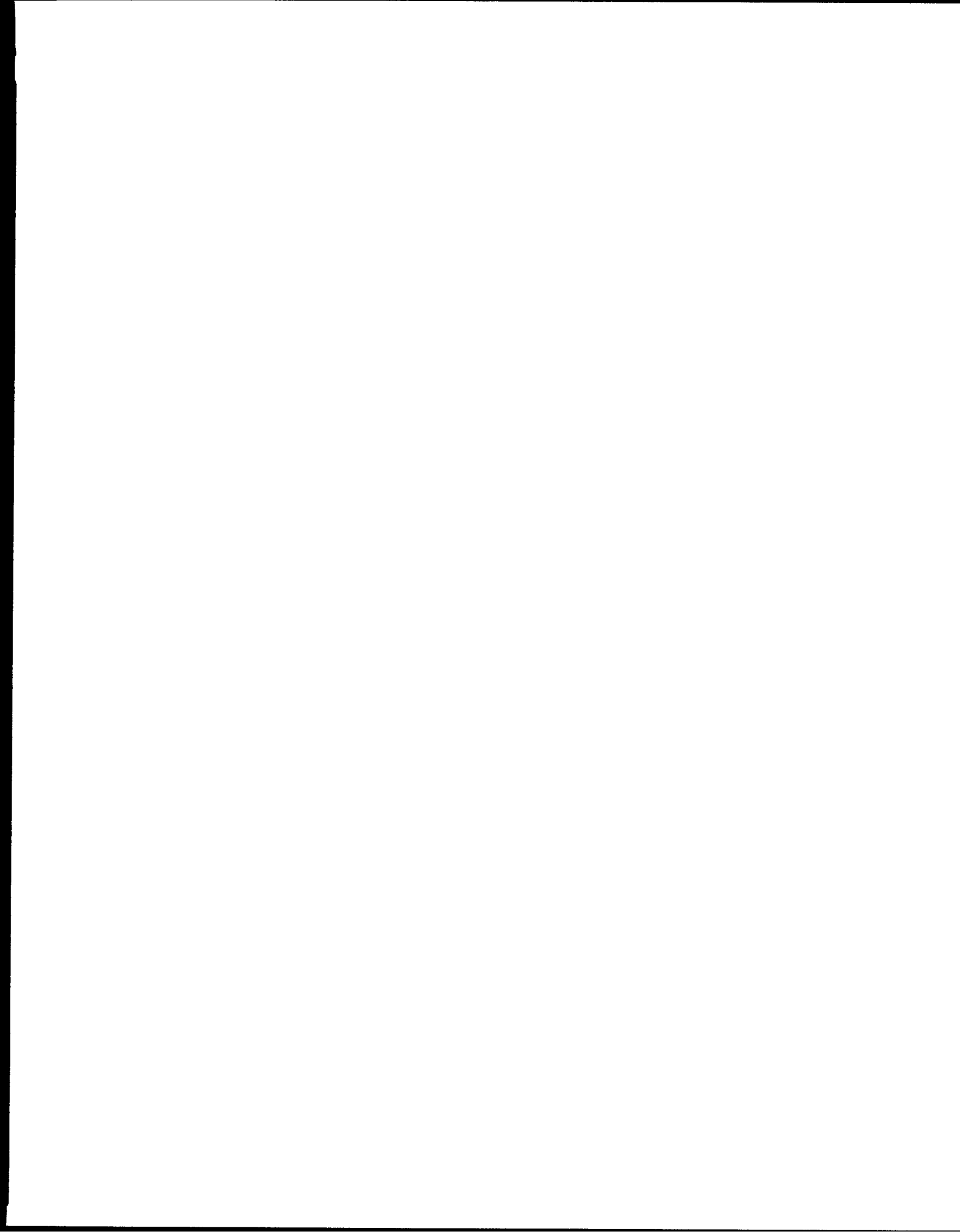


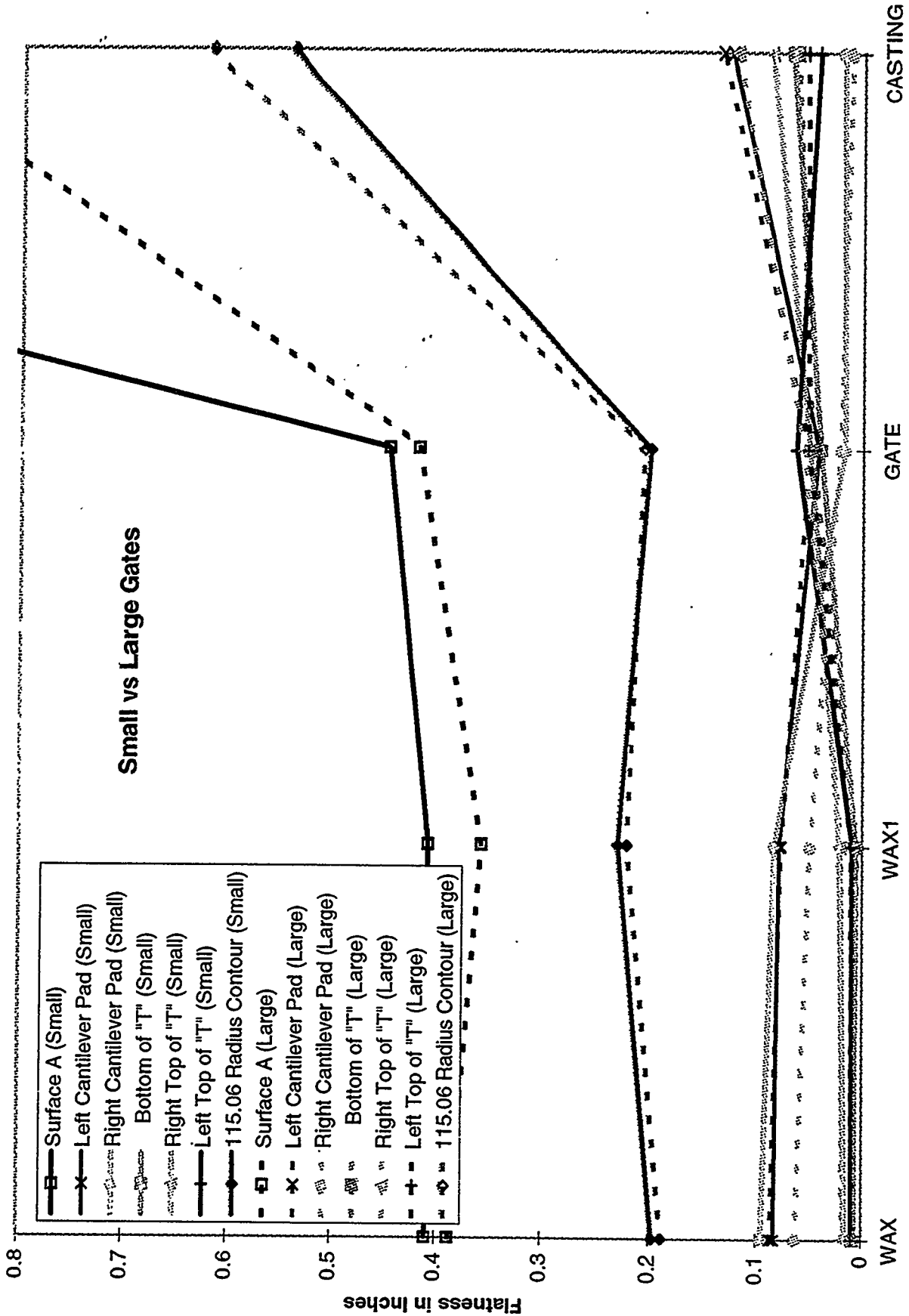


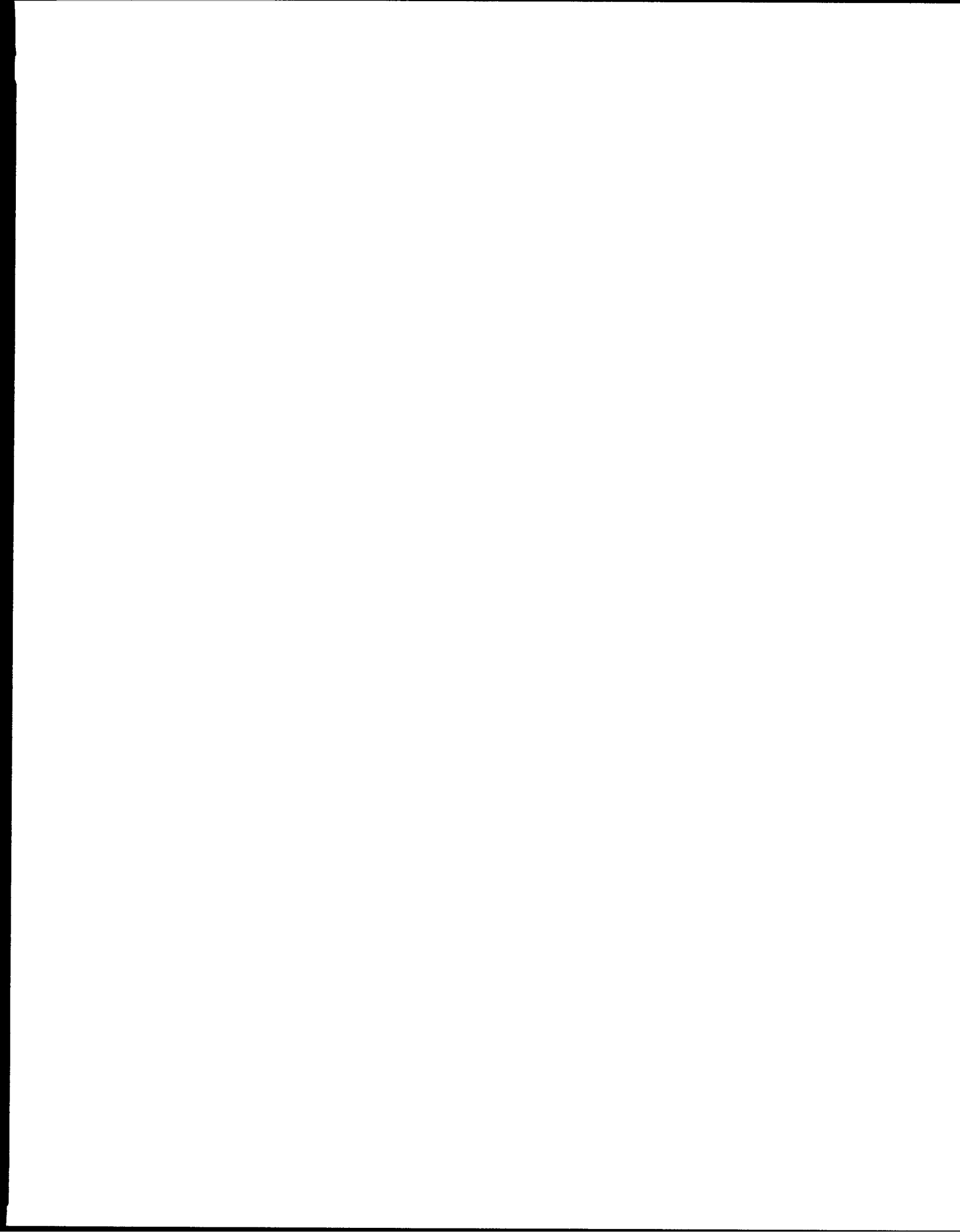


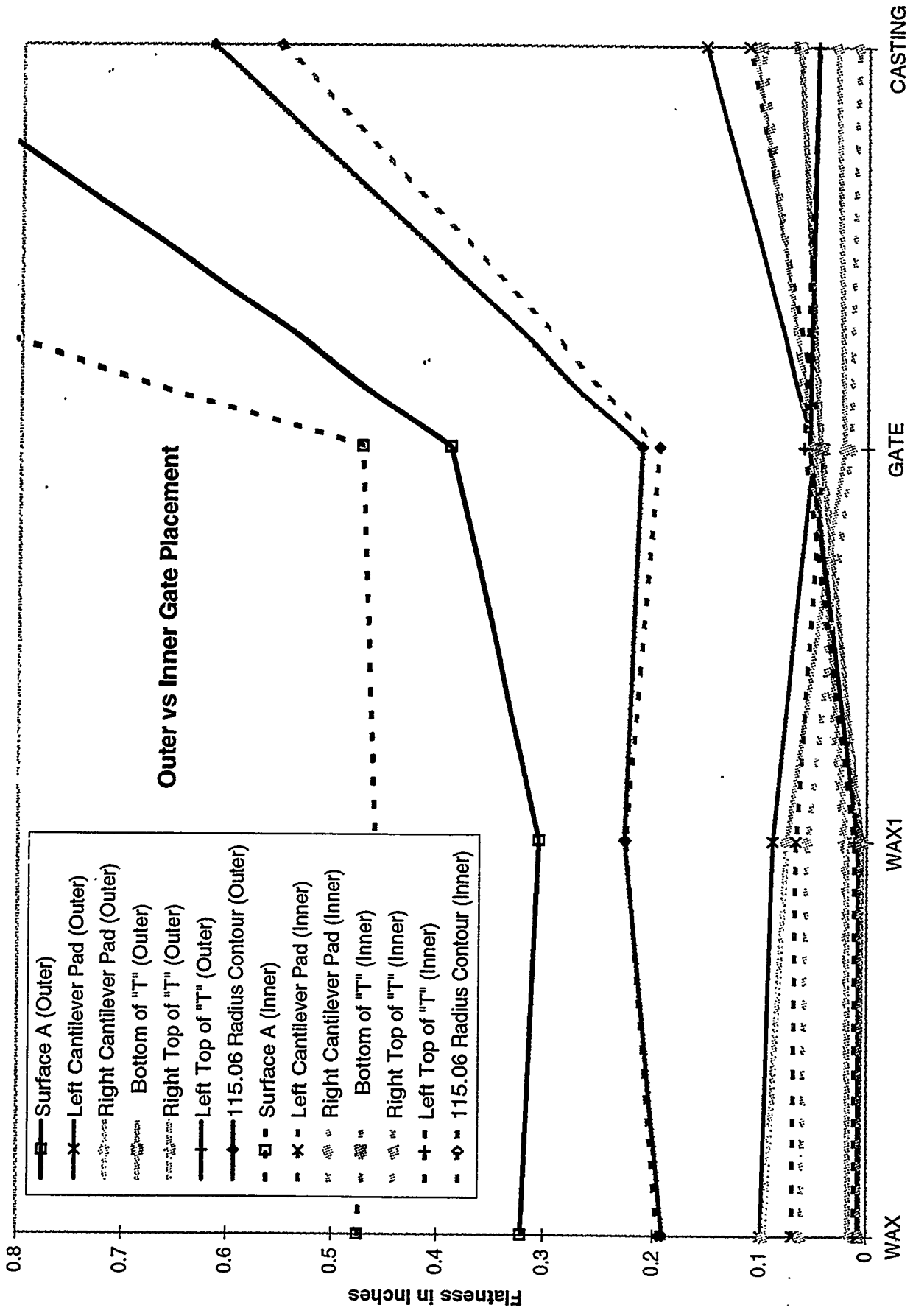


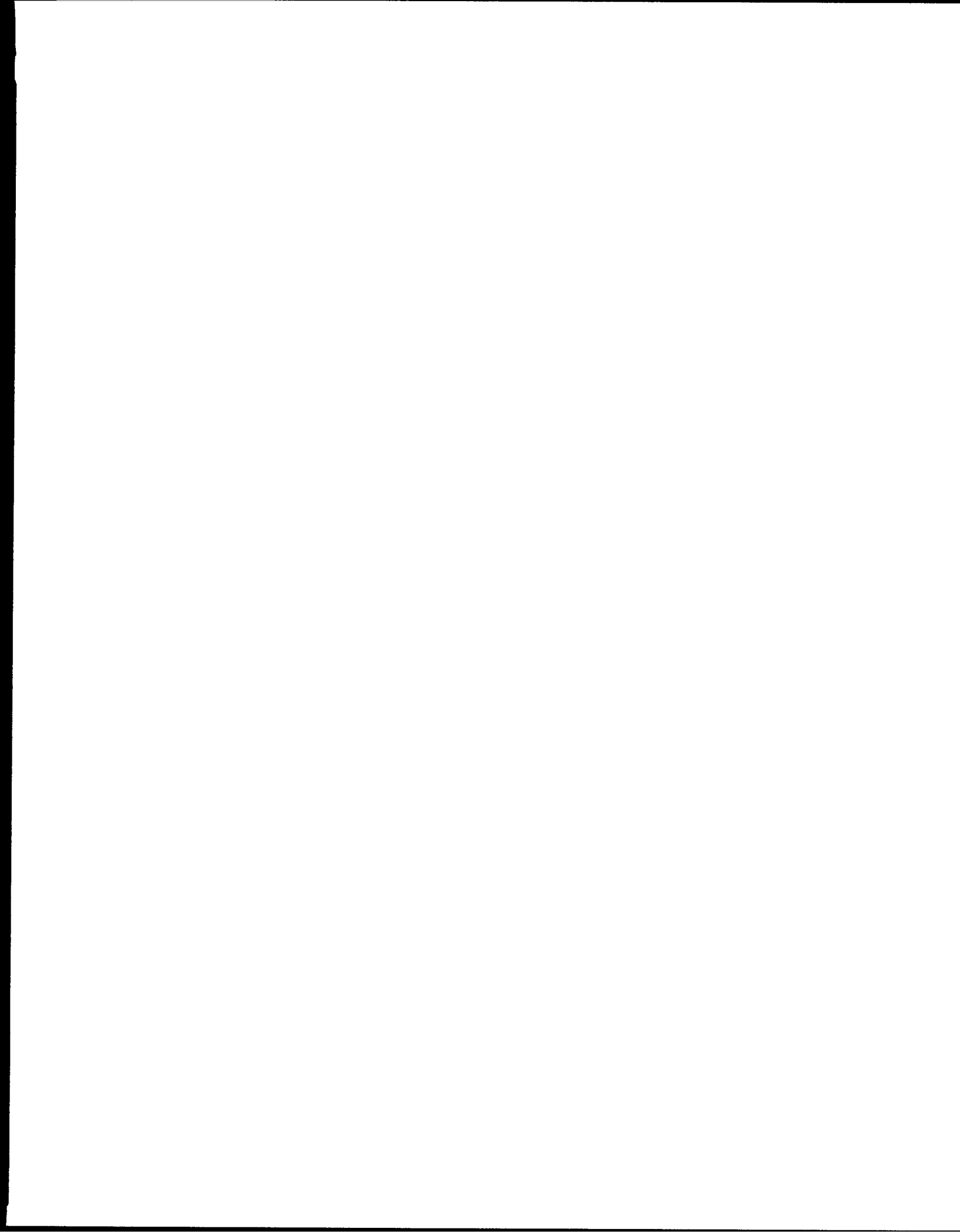


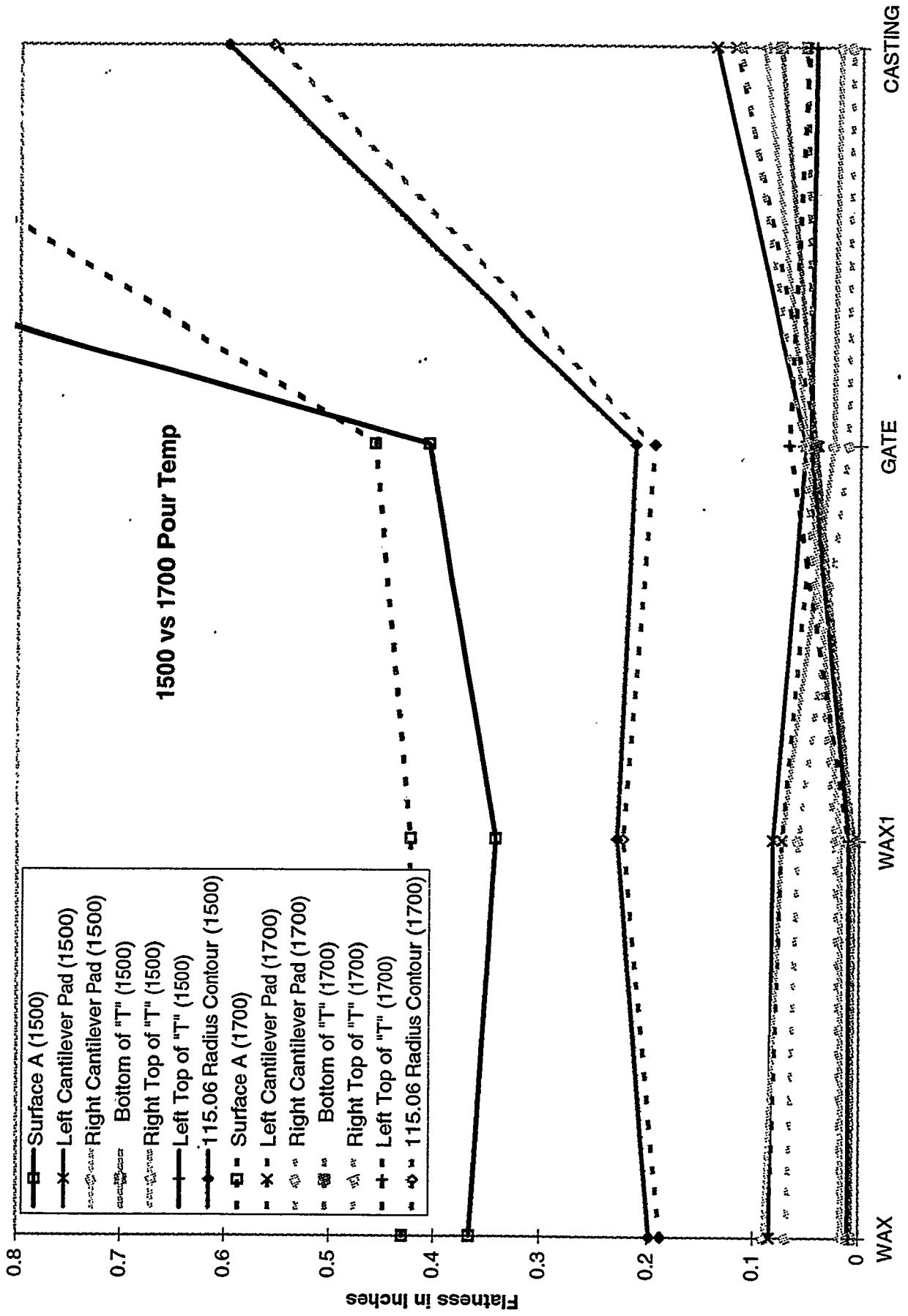


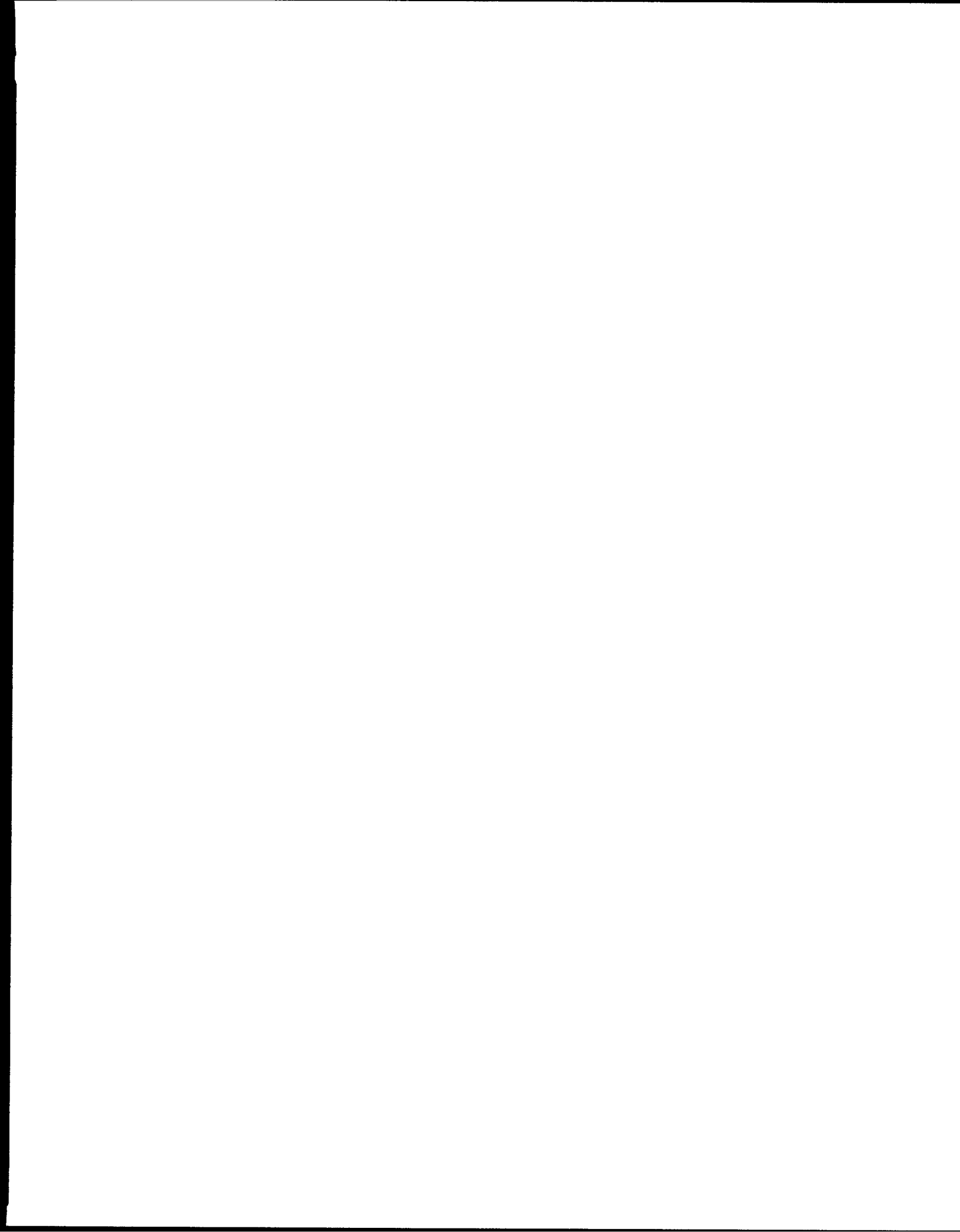


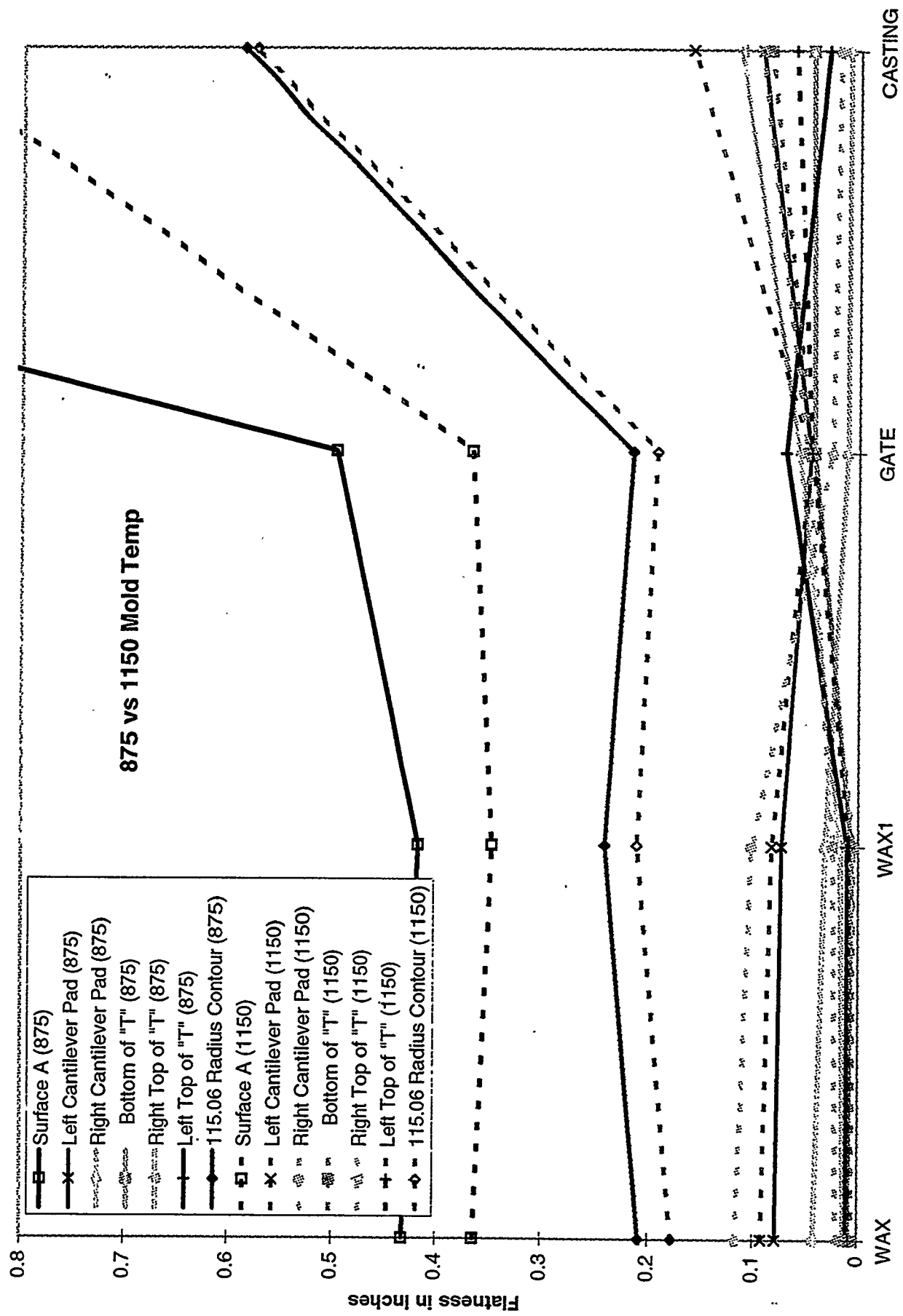


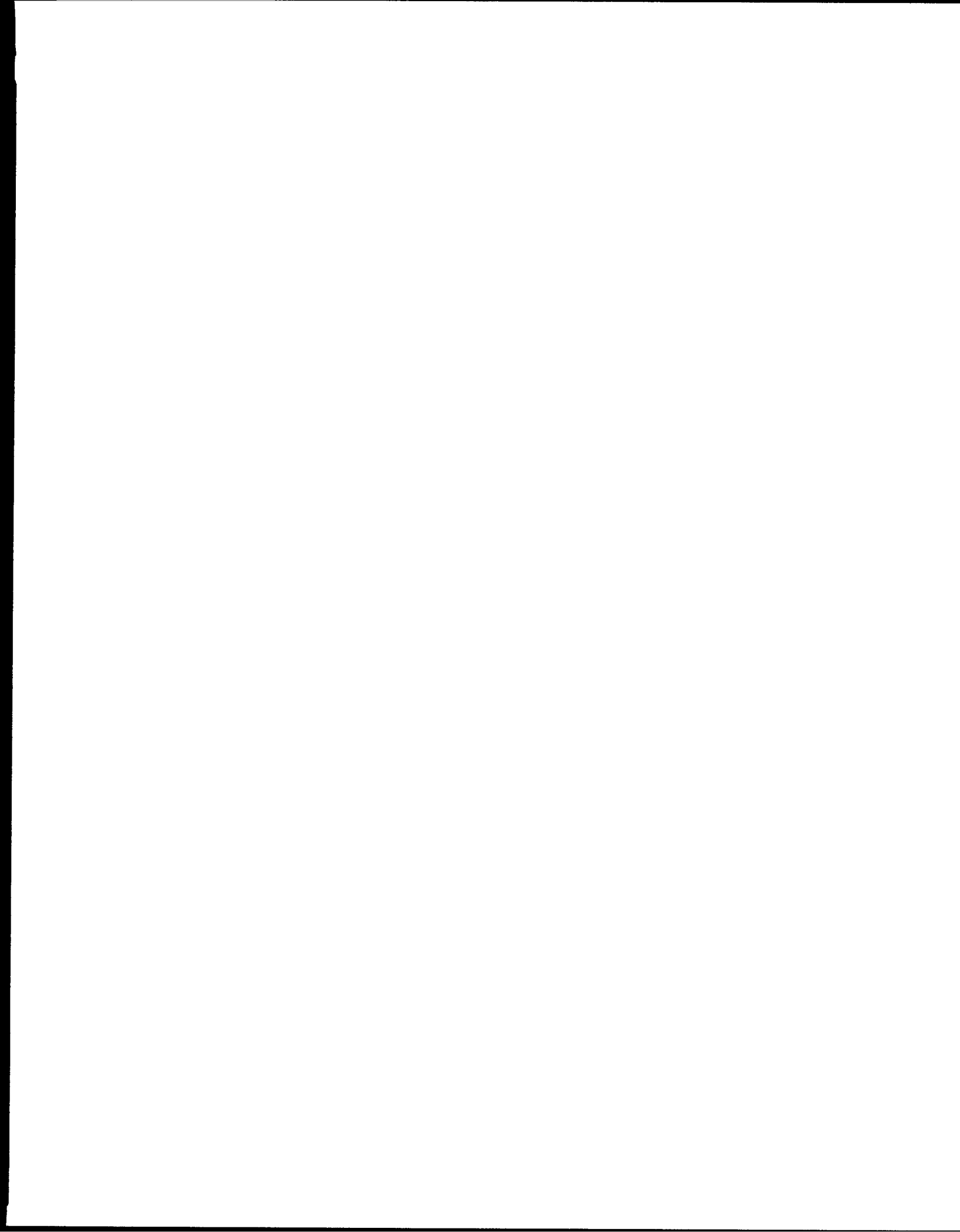


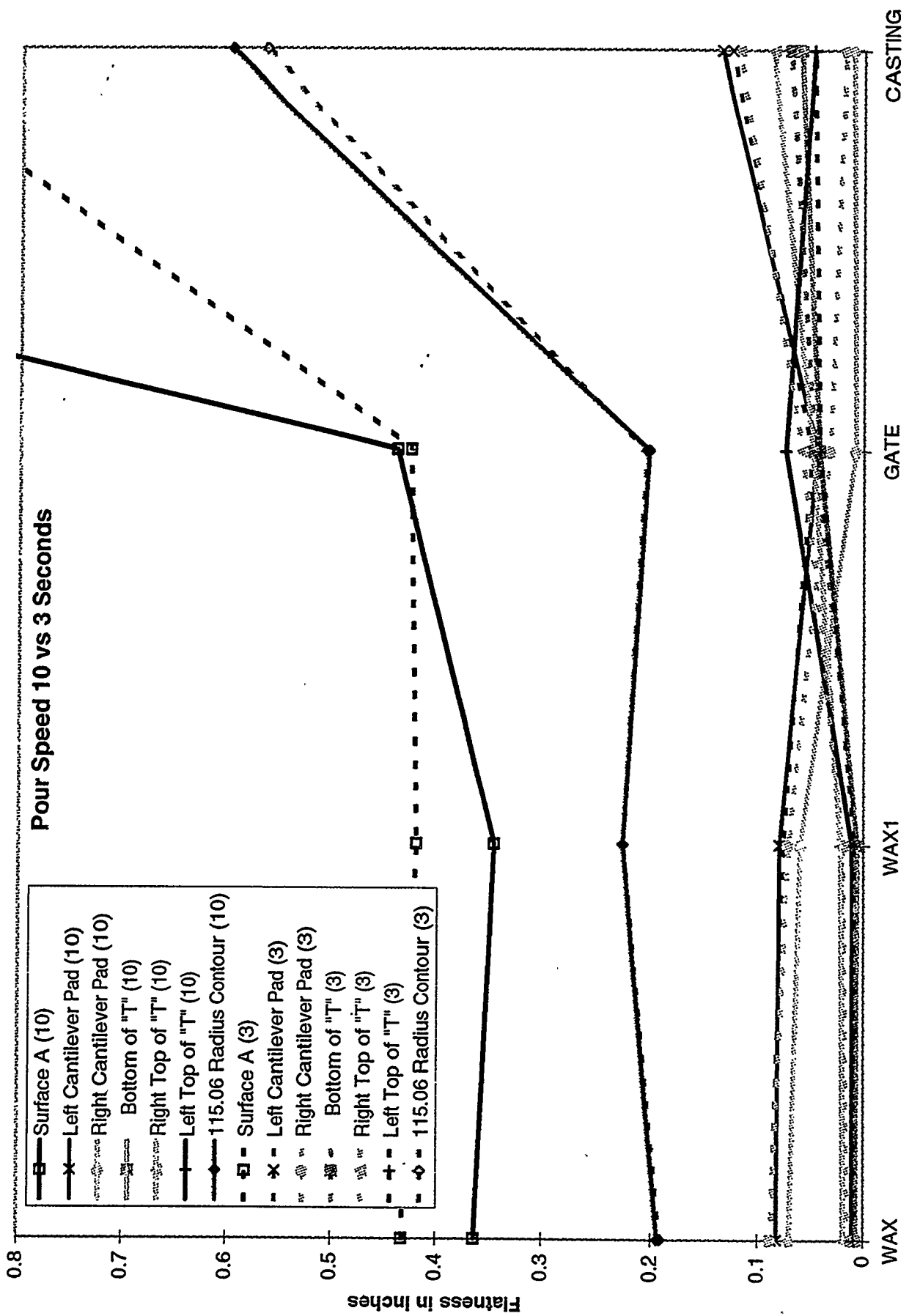


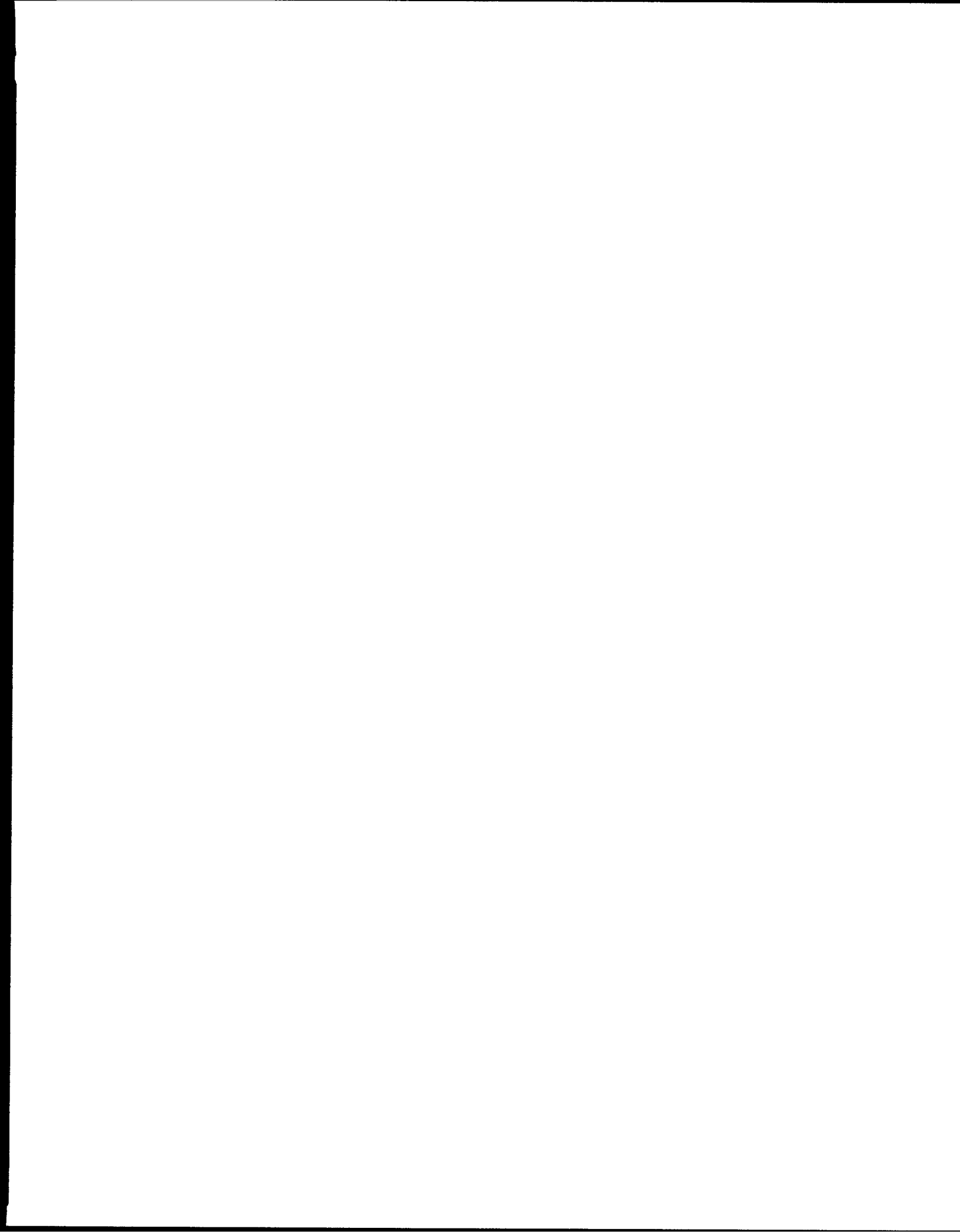


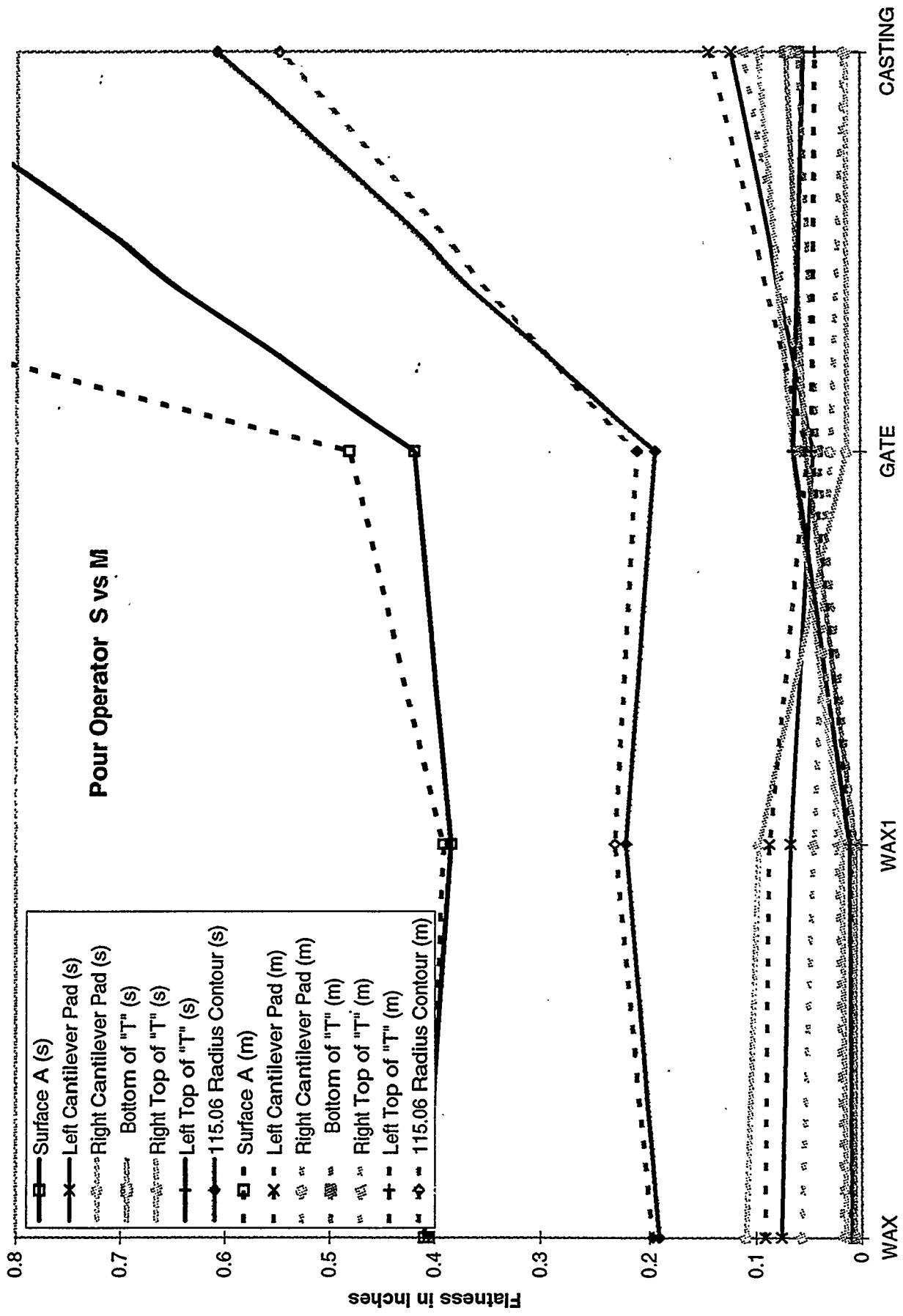


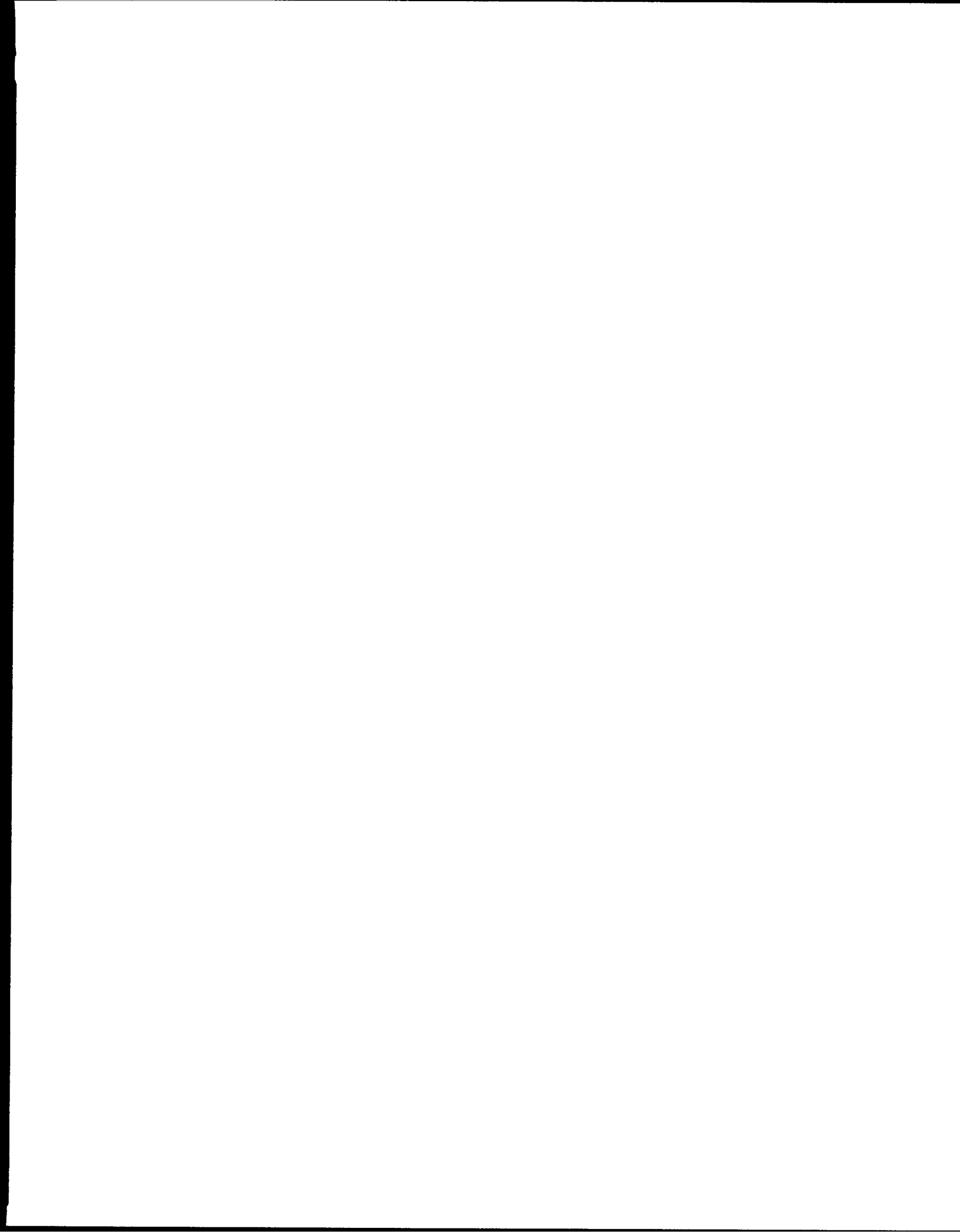




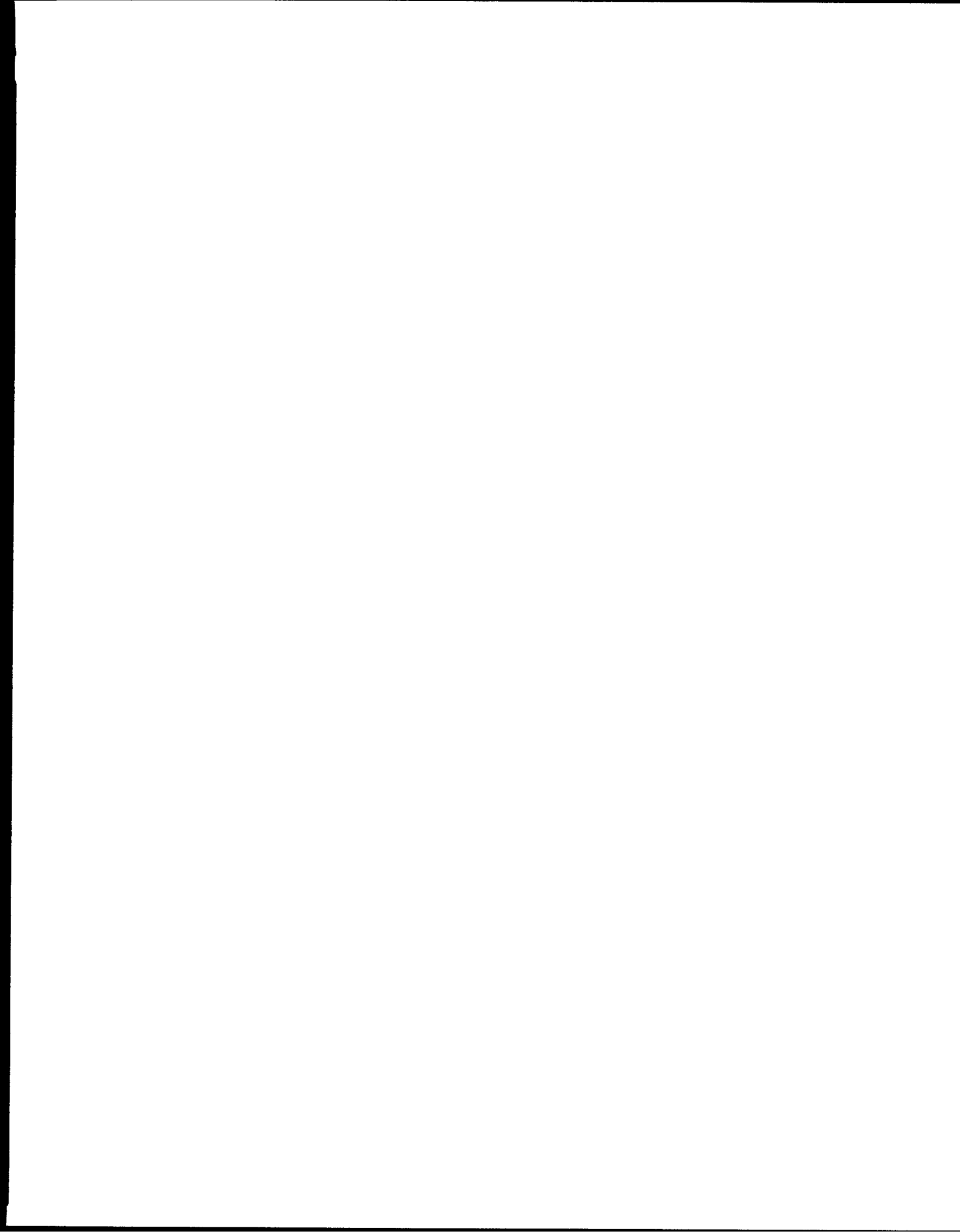












**APPENDIX B**

**Raw Dimensional Data**

Raw Dimensional Data

| Part # | Dimension                            |        | Left Cantilever Pad |        | Right Cantilever Pad |        | Bottom of "T" |        | Right Top of "T" |        | Left Top of "T" |        | 115.06 R<br>CONTOUR |
|--------|--------------------------------------|--------|---------------------|--------|----------------------|--------|---------------|--------|------------------|--------|-----------------|--------|---------------------|
|        | Surface A                            |        | FLATNESS            | ST DEV | FLATNESS             | ST DEV | FLATNESS      | ST DEV | FLATNESS         | ST DEV | FLATNESS        | ST DEV |                     |
|        | FLATNES                              | ST DEV | FLATNESS            | ST DEV | FLATNESS             | ST DEV | FLATNESS      | ST DEV | FLATNESS         | ST DEV | FLATNES         | ST DEV |                     |
| 01'    | 0.409                                | 0.162  | 0.071               | 0.038  | 0.006                | 0.003  | 0.004         | 0.004  | 0.006            | 0.005  | 0.008           | 0.007  | 0.206               |
| 01A    | 0.286                                | 0.126  | 0.065               | 0.035  | 0.006                | 0.004  | 0.006         | 0.005  | 0.002            | 0.002  | 0.01            | 0.009  | 0.246               |
| 01B    | 0.304                                | 0.134  | 0.037               | 0.021  | 0.008                | 0.005  | 0.002         | 0.002  | 0.022            | 0.019  | 0.092           | 0.083  | 0.245               |
| 1C     | NON-FILL OR TOO DISTORTED TO MEASURE |        |                     |        |                      |        |               |        |                  |        |                 |        |                     |
| 02'    | 0.347                                | 0.138  | 0.076               | 0.041  | 0.004                | 0.003  | 0.008         | 0.007  | 0.004            | 0.003  | 0.002           | 0.002  | 0.221               |
| 02A    | 0.239                                | 0.1    | 0.07                | 0.037  | 0.004                | 0.003  | 0.006         | 0.006  | 0.006            | 0.006  | 0.004           | 0.003  | 0.243               |
| 02B    | 0.625                                | 0.291  | 0.055               | 0.031  | 0.018                | 0.011  | 0.004         | 0.004  | 0.014            | 0.012  | 0.064           | 0.058  | 0.248               |
| 2C     | NON-FILL OR TOO DISTORTED TO MEASURE |        |                     |        |                      |        |               |        |                  |        |                 |        |                     |
| 03'    | 0.386                                | 0.156  | 0.072               | 0.038  | 0.002                | 0.001  | 0.02          | 0.019  | 0.028            | 0.023  | 0.024           | 0.021  | 0.239               |
| 03A    | 0.281                                | 0.121  | 0.07                | 0.037  | 0.002                | 0.001  | 0.012         | 0.013  | 0.024            | 0.021  | 0.024           | 0.022  | 0.265               |
| 03B    | 0.442                                | 0.201  | 0.054               | 0.029  | 0.002                | 0.002  | 0.068         | 0.067  | 0.042            | 0.035  | 0.06            | 0.054  | 0.264               |
| 03C    | 1.629                                | 0.81   | 0.11                | 0.061  | 0.022                | 0.013  | 0.06          | 0.06   | 0.016            | 0.014  | 0.008           | 0.007  | 1.019               |
| 04'    | 0.321                                | 0.128  | 0.074               | 0.039  | 0.002                | 0.001  | 0.01          | 0.009  | 0.01             | 0.009  | 0.004           | 0.004  | 0.219               |
| 04A    | 0.36                                 | 0.142  | 0.068               | 0.036  | 0.002                | 0.001  | NA            | 0.001  | 0.012            | 0.01   | 0.002           | 0.002  | 0.25                |
| 04B    | 0.505                                | 0.263  | 0.051               | 0.028  | 0.002                | 0.001  | 0.028         | 0.028  | 0.006            | 0.004  | 0.086           | 0.078  | 0.252               |
| 04C    | -12.667                              | .255   | 0.083               | 0.047  | 0.002                | 0.002  | 0.032         | 0.031  | 0.098            | 0.084  | 0.024           | 0.022  | 0.77                |
| 05'    | 0.313                                | 0.123  | 0.104               | 0.058  | 0.043                | 0.026  | 0.004         | 0.004  | 0.006            | 0.006  | 0.002           | 0.002  | 0.162               |
| 05A    | 0.338                                | 0.133  | 0.107               | 0.06   | 0.028                | 0.016  | 0.002         | 0.001  | 0.016            | 0.014  | 0.002           | 0.001  | 0.198               |
| 05B    | 0.199                                | 0.085  | NA                  | NA     | NA                   | NA     | 0.088         | 0.087  | 0.072            | 0.062  | NA              | NA     | 0.166               |
| 05C    | 0.501                                | 0.259  | NA                  | NA     | NA                   | NA     | 0.012         | 0.011  | 0.18             | 0.153  | NA              | NA     | 0.378               |
| 06'    | 0.264                                | 0.108  | 0.038               | 0.022  | 0.006                | 0.003  | 0.018         | 0.018  | 0.01             | 0.009  | 0.01            | 0.008  | 0.278               |
| 06A    | 0.305                                | 0.126  | 0.034               | 0.019  | 0.008                | 0.004  | 0.02          | 0.02   | 0.016            | 0.014  | 0.004           | 0.004  | 0.307               |
| 06B    | 0.41                                 | 0.206  | NA                  | NA     | NA                   | NA     | 0.068         | 0.067  | 0.11             | 0.094  | NA              | NA     | 0.222               |
| 06C    | 1.016                                | 0.505  | NA                  | NA     | NA                   | NA     | 0.008         | 0.008  | 0.196            | 0.167  | NA              | NA     | 0.462               |
| 07'    | 0.368                                | 0.145  | 0.03                | 0.016  | 0.138                | 0.082  | 0.002         | 0.002  | 0.014            | 0.011  | 0.002           | 0.001  | 0.209               |
| 07A    | 0.342                                | 0.141  | 0.028               | 0.015  | 0.116                | 0.069  | 0.002         | 0.002  | 0.018            | 0.015  | 0.006           | 0.006  | 0.242               |
| 07B    | 0.477                                | 0.212  | NA                  | NA     | NA                   | NA     | 0.028         | 0.028  | 0.06             | 0.051  | NA              | NA     | 0.191               |
| 07C    | 0.79                                 | 0.35   | NA                  | NA     | NA                   | NA     | 0.108         | 0.107  | 0.052            | 0.045  | NA              | NA     | 0.538               |
| 08'    | 0.181                                | 0.077  | 0.091               | 0.048  | 0.004                | 0.003  | NA            | 0.001  | 0.012            | 0.011  | 0.026           | 0.024  | 0.181               |
| 08A    | 0.232                                | 0.094  | 0.083               | 0.044  | 0.007                | 0.004  | 0.002         | 0.003  | 0.01             | 0.009  | 0.01            | 0.008  | 0.217               |
| 08B    | 0.256                                | 0.134  | NA                  | NA     | NA                   | NA     | 0.028         | 0.028  | 0.07             | 0.06   | NA              | NA     | 0.248               |
| 08C    | 0.554                                | 0.242  | NA                  | NA     | NA                   | NA     | 0.012         | 0.013  | 0.214            | 0.182  | NA              | NA     | 0.473               |
| 09'    | 0.289                                | 0.119  | 0.063               | 0.033  | 0.091                | 0.054  | 0.002         | 0.001  | 0.024            | 0.02   | 0.016           | 0.015  | 0.16                |
| 09A    | 0.297                                | 0.126  | 0.06                | 0.032  | 0.078                | 0.046  | 0.008         | 0.008  | 0.034            | 0.03   | 0.01            | 0.009  | 0.189               |
| 09B    | 0.224                                | 0.104  | NA                  | NA     | NA                   | NA     | 0.036         | 0.035  | 0.048            | 0.04   | NA              | NA     | 0.138               |
| 09C    | 0.781                                | 0.32   | NA                  | NA     | NA                   | NA     | NA            | 0.001  | 0.088            | 0.075  | NA              | NA     | 0.384               |
| 10'    | 0.356                                | 0.142  | 0.036               | 0.021  | 0.004                | 0.003  | 0.006         | 0.007  | 0.02             | 0.016  | 0.006           | 0.006  | 0.196               |
| 10A    | 0.353                                | 0.148  | 0.042               | 0.024  | 0.005                | 0.003  | 0.004         | 0.004  | 0.02             | 0.017  | 0.008           | 0.007  | 0.226               |
| 10B    | 0.216                                | 0.09   | NA                  | NA     | NA                   | NA     | 0.032         | 0.031  | 0.094            | 0.08   | NA              | NA     | 0.173               |
| 10C    | 1.55                                 | 0.712  | NA                  | NA     | NA                   | NA     | 0.044         | 0.043  | 0.168            | 0.143  | NA              | NA     | 0.329               |
| 11'    | 0.375                                | 0.15   | 0.08                | 0.044  | 0.405                | 0.239  | 0.012         | 0.011  | NA               | NA     | 0.006           | 0.006  | 0.174               |
| 11A    | 0.37                                 | 0.152  | 0.084               | 0.045  | 0.369                | 0.218  | NA            | 0.001  | 0.01             | 0.008  | 0.016           | 0.014  | 0.188               |
| 11B    | 0.533                                | 0.26   | NA                  | NA     | NA                   | NA     | 0.128         | 0.125  | 0.086            | 0.073  | NA              | NA     | 0.182               |
| 11C    | 0.597                                | 0.278  | NA                  | NA     | NA                   | NA     | 0.118         | 0.116  | 0.082            | 0.069  | NA              | NA     | 0.497               |
| 12'    | 0.311                                | 0.128  | 0.218               | 0.117  | 0.151                | 0.089  | NA            | 0.001  | 0.034            | 0.028  | 0.002           | 0.003  | 0.18                |
| 12A    | 0.344                                | 0.145  | 0.204               | 0.11   | 0.106                | 0.063  | NA            | NA     | 0.042            | 0.035  | 0.012           | 0.012  | 0.219               |
| 12B    | 0.418                                | 0.208  | NA                  | NA     | NA                   | NA     | 0.074         | 0.073  | 0.072            | 0.062  | NA              | NA     | 0.187               |
| 12C    | 0.653                                | 0.277  | NA                  | NA     | NA                   | NA     | 0.034         | 0.034  | 0.042            | 0.035  | NA              | NA     | 0.481               |
| 13'    | 0.363                                | 0.154  | 0.123               | 0.074  | 0.116                | 0.068  | 0.008         | 0.007  | 0.02             | 0.018  | NA              | 0.001  | 0.19                |
| 13A    | 0.256                                | 0.109  | 0.13                | 0.078  | 0.042                | 0.025  | 0.006         | 0.005  | 0.022            | 0.02   | 0.008           | 0.008  | 0.231               |
| 13B    | 0.374                                | 0.16   | 0.085               | 0.048  | 0.018                | 0.011  | 0.04          | 0.039  | NA               | NA     | 0.012           | 0.011  | 0.239               |
| 13C    | 0.85                                 | 0.403  | 0.176               | 0.094  | 0.016                | 0.01   | 0.112         | 0.109  | 0.104            | 0.088  | 0.098           | 0.088  | 0.994               |
| 14'    | 0.331                                | 0.141  | 0.14                | 0.074  | 0.171                | 0.101  | 0.006         | 0.006  | 0.022            | 0.018  | 0.02            | 0.017  | 0.217               |
| 14A    | 0.326                                | 0.136  | 0.134               | 0.071  | 0.142                | 0.084  | 0.004         | 0.004  | 0.026            | 0.023  | 0.022           | 0.021  | 0.24                |
| 14B    | 0.413                                | 0.196  | 0.053               | 0.029  | 0.083                | 0.049  | 0.04          | 0.04   | 0.02             | 0.017  | 0.014           | 0.012  | 0.253               |
| 14C    | 1.272                                | 0.615  | 0.236               | 0.135  | 0.059                | 0.035  | 0.132         | 0.129  | 0.004            | 0.004  | 0.018           | 0.017  | 0.809               |
| 15'    | 0.696                                | 0.305  | 0.077               | 0.041  | 0.237                | 0.14   | 0.002         | 0.002  | 0.002            | 0.001  | NA              | NA     | 0.166               |
| 15A    | 0.7                                  | 0.305  | 0.07                | 0.037  | 0.214                | 0.127  | 0.004         | 0.004  | 0.008            | 0.007  | 0.01            | 0.009  | 0.178               |
| 15B    | 0.518                                | 0.263  | 0.024               | 0.013  | 0.014                | 0.009  | 0.016         | 0.016  | 0.026            | 0.022  | 0.044           | 0.04   | 0.183               |
| 15C    | 1.267                                | 0.5    | 0.1                 | 0.056  | 0.017                | 0.01   | 0.116         | 0.113  | 0.012            | 0.01   | 0.004           | 0.004  | 0.637               |

Raw Dimensional Data

|     |                                      |       |       |       |       |       |       |       |       |       |       |       |       |
|-----|--------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 16' | 0.558                                | 0.231 | 0.06  | 0.034 | 0.055 | 0.032 | 0.006 | 0.005 | 0.03  | 0.025 | 0.01  | 0.009 | 0.171 |
| 16A | 0.457                                | 0.192 | 0.059 | 0.033 | 0.041 | 0.025 | 0.002 | 0.003 | 0.03  | 0.025 | 0.002 | 0.002 | 0.216 |
| 16B | 0.588                                | 0.276 | 0.055 | 0.031 | 0.057 | 0.034 | 0.004 | 0.004 | 0.014 | 0.012 | 0.004 | 0.003 | 0.213 |
| 16C | 0.553                                | 0.249 | 0.125 | 0.067 | 0.002 | 0.001 | 0.214 | 0.21  | 0.046 | 0.04  | 0.106 | 0.096 | 0.651 |
| 17' | 0.331                                | 0.136 | 0.101 | 0.054 | 0.19  | 0.112 | 0.01  | 0.009 | 0.026 | 0.022 | 0.012 | 0.01  | 0.188 |
| 17A | 0.307                                | 0.133 | 0.102 | 0.054 | 0.136 | 0.08  | 0.008 | 0.007 | 0.024 | 0.021 | 0.004 | 0.003 | 0.212 |
| 17B | 0.587                                | 0.293 | NA    | NA    | NA    | NA    | 0.092 | 0.09  | 0.1   | 0.086 | NA    | NA    | 0.151 |
| 17C | NON-FILL OR TOO DISTORTED TO MEASURE |       |       |       |       |       |       |       |       |       |       |       |       |
| 18' | 0.341                                | 0.142 | 0.04  | 0.023 | 0.201 | 0.119 | 0.01  | 0.01  | 0.022 | 0.02  | 0.006 | 0.006 | 0.18  |
| 18A | 0.337                                | 0.14  | 0.044 | 0.023 | 0.153 | 0.091 | 0.002 | 0.001 | 0.026 | 0.023 | 0.004 | 0.004 | 0.22  |
| 18B | 0.653                                | 0.321 | NA    | NA    | NA    | NA    | 0.078 | 0.076 | 0.072 | 0.061 | NA    | NA    | 0.189 |
| 18C | 1.32                                 | 0.604 | NA    | NA    | NA    | NA    | 0.024 | 0.023 | 0.122 | 0.105 | NA    | NA    | 0.708 |
| 19' | 0.49                                 | 0.206 | 0.088 | 0.046 | 0.009 | 0.005 | 0.002 | 0.002 | 0.01  | 0.009 | 0.026 | 0.023 | 0.224 |
| 19A | 0.476                                | 0.198 | 0.082 | 0.044 | 0.006 | 0.004 | 0.006 | 0.006 | 0.022 | 0.018 | 0.036 | 0.033 | 0.245 |
| 19B | 0.39                                 | 0.198 | NA    | NA    | NA    | NA    | 0.034 | 0.033 | 0.052 | 0.045 | NA    | NA    | 0.185 |
| 19C | 0.709                                | 0.304 | NA    | NA    | NA    | NA    | 0.002 | 0.003 | 0.108 | 0.093 | NA    | NA    | 0.5   |
| 20' | 0.605                                | 0.28  | 0.088 | 0.047 | 0.016 | 0.01  | 0.006 | 0.007 | 0.012 | 0.011 | 0.028 | 0.026 | 0.22  |
| 20A | 0.675                                | 0.303 | 0.081 | 0.043 | 0.008 | 0.005 | 0.004 | 0.004 | 0.022 | 0.019 | 0.024 | 0.022 | 0.253 |
| 20B | 0.718                                | 0.323 | NA    | NA    | NA    | NA    | 0.008 | 0.007 | 0.072 | 0.061 | NA    | NA    | 0.162 |
| 20C | 0.909                                | 0.388 | NA    | NA    | NA    | NA    | 0.12  | 0.118 | 0.064 | 0.055 | NA    | NA    | 0.403 |
| 21' | 0.817                                | 0.364 | 0.078 | 0.041 | 0.029 | 0.017 | 0.01  | 0.011 | 0.018 | 0.016 | 0.004 | 0.004 | 0.207 |
| 21A | 0.762                                | 0.345 | 0.069 | 0.037 | 0.014 | 0.008 | 0.006 | 0.006 | 0.018 | 0.015 | NA    | 0.001 | 0.237 |
| 21B | 0.676                                | 0.333 | 0.031 | 0.018 | 0.039 | 0.023 | NA    | NA    | 0.154 | 0.131 | 0.118 | 0.106 | 0.224 |
| 21C | 1.343                                | 0.532 | 0.033 | 0.02  | 0.004 | 0.003 | 0.136 | 0.133 | 0.064 | 0.054 | 0.03  | 0.027 | 0.858 |
| 22' | 1.061                                | 0.458 | 0.114 | 0.061 | 0.006 | 0.003 | 0.01  | 0.01  | 0.016 | 0.013 | 0.006 | 0.005 | 0.205 |
| 22A | 1.054                                | 0.453 | 0.098 | 0.053 | 0.006 | 0.004 | 0.008 | 0.007 | 0.03  | 0.026 | 0.014 | 0.013 | 0.24  |
| 22B | 0.85                                 | 0.341 | 0.043 | 0.024 | 0.004 | 0.002 | 0.022 | 0.022 | 0.01  | 0.009 | 0.036 | 0.033 | 0.212 |
| 22C | 1.851                                | 0.747 | 0.057 | 0.032 | 0.008 | 0.005 | 0.028 | 0.027 | 0.106 | 0.091 | 0.028 | 0.026 | 0.173 |
| 23' | 0.293                                | 0.123 | 0.077 | 0.041 | 0.005 | 0.003 | 0.01  | 0.01  | 0.006 | 0.006 | 0.006 | 0.006 | 0.191 |
| 23A | 0.312                                | 0.127 | 0.069 | 0.037 | 0.006 | 0.004 | 0.002 | 0.002 | 0.012 | 0.01  | 0.014 | 0.012 | 0.237 |
| 23B | 0.372                                | 0.177 | 0.051 | 0.028 | 0.004 | 0.003 | 0.026 | 0.025 | 0.012 | 0.01  | 0.072 | 0.065 | 0.215 |
| 23C | 1.195                                | 0.561 | 0.098 | 0.059 | NA    | NA    | 0.014 | 0.014 | 0.154 | 0.131 | 0.086 | 0.078 | 0.601 |
| 24' | 0.379                                | 0.157 | 0.106 | 0.056 | 0.004 | 0.003 | 0.014 | 0.013 | 0.01  | 0.008 | 0.002 | 0.002 | 0.207 |
| 24A | 0.374                                | 0.152 | 0.097 | 0.052 | 0.004 | 0.002 | 0.01  | 0.011 | 0.012 | 0.01  | 0.002 | 0.001 | 0.24  |
| 24B | 0.495                                | 0.22  | 0.046 | 0.025 | NA    | NA    | 0.064 | 0.062 | 0.036 | 0.031 | 0.03  | 0.028 | 0.267 |
| 24C | 1.461                                | 0.688 | 0.176 | 0.097 | 0.012 | 0.007 | 0.028 | 0.028 | 0.112 | 0.096 | 0.002 | 0.002 | 0.747 |
| 25' | 0.352                                | 0.155 | 0.028 | 0.016 | 0.004 | 0.002 | 0.002 | 0.001 | 0.018 | 0.015 | 0.002 | 0.002 | 0.171 |
| 25A | 0.367                                | 0.153 | 0.036 | 0.02  | NA    | 0.001 | NA    | 0.001 | 0.022 | 0.019 | 0.002 | 0.003 | 0.196 |
| 25B | 0.692                                | 0.338 | 0.033 | 0.019 | 0.004 | 0.002 | 0.038 | 0.037 | 0.006 | 0.006 | 0.044 | 0.04  | 0.217 |
| 25C | 1.77                                 | 0.895 | 0.216 | 0.119 | 0.008 | 0.005 | 0.064 | 0.064 | 0.042 | 0.036 | 0.096 | 0.086 | 0.735 |
| 26' | 0.393                                | 0.162 | 0.083 | 0.044 | 0.006 | 0.003 | 0.012 | 0.012 | 0.022 | 0.018 | 0.006 | 0.006 | 0.163 |
| 26A | 0.24                                 | 0.096 | 0.076 | 0.04  | 0.005 | 0.003 | 0.002 | 0.001 | 0.03  | 0.025 | 0.014 | 0.012 | 0.218 |
| 26B | 0.401                                | 0.208 | 0.042 | 0.024 | 0.004 | 0.002 | 0.018 | 0.018 | 0.004 | 0.003 | 0.086 | 0.078 | 0.203 |
| 26C | 0.876                                | 0.426 | 0.181 | 0.1   | 0.008 | 0.004 | 0.06  | 0.06  | 0.09  | 0.077 | 0.074 | 0.066 | 0.749 |
| 27' | 0.311                                | 0.128 | 0.101 | 0.054 | 0.006 | 0.004 | 0.002 | 0.002 | 0.02  | 0.017 | 0.004 | 0.004 | 0.184 |
| 27A | 0.314                                | 0.134 | 0.094 | 0.05  | 0.006 | 0.003 | 0.002 | 0.002 | 0.028 | 0.023 | 0.002 | 0.002 | 0.225 |
| 27B | 0.19                                 | 0.082 | 0.035 | 0.021 | 0.007 | 0.004 | 0.002 | 0.002 | 0.026 | 0.022 | 0.038 | 0.035 | 0.227 |
| 27C | NON-FILL OR TOO DISTORTED TO MEASURE |       |       |       |       |       |       |       |       |       |       |       |       |
| 28' | 0.21                                 | 0.089 | 0.099 | 0.052 | 0.023 | 0.013 | 0.002 | 0.003 | 0.024 | 0.021 | 0.01  | 0.009 | 0.181 |
| 28A | 0.293                                | 0.115 | 0.09  | 0.048 | 0.006 | 0.003 | 0.008 | 0.008 | 0.022 | 0.019 | 0.004 | 0.004 | 0.218 |
| 28B | 0.125                                | 0.06  | 0.041 | 0.023 | 0.014 | 0.008 | 0.026 | 0.025 | 0.054 | 0.045 | 0.118 | 0.107 | 0.223 |
| 28C | 0.969                                | 0.455 | 0.083 | 0.046 | NA    | 0.001 | 0.094 | 0.091 | 0.112 | 0.096 | 0.032 | 0.029 | 0.609 |
| 29' | 0.271                                | 0.111 | 0.14  | 0.075 | 0.006 | 0.004 | 0.004 | 0.004 | 0.018 | 0.015 | 0.002 | 0.002 | 0.179 |
| 29A | 0.337                                | 0.142 | 0.017 | 0.01  | 0.008 | 0.005 | 0.004 | 0.003 | 0.018 | 0.015 | 0.008 | 0.007 | 0.22  |
| 29B | 0.196                                | 0.091 | NA    | NA    | NA    | NA    | 0.038 | 0.038 | 0.066 | 0.056 | NA    | NA    | 0.136 |
| 29C | 0.702                                | 0.329 | NA    | NA    | NA    | NA    | 0.032 | 0.032 | 0.19  | 0.163 | NA    | NA    | 0.352 |
| 30' | 0.316                                | 0.125 | 0.106 | 0.057 | 0.116 | 0.068 | 0.006 | 0.006 | 0.02  | 0.017 | 0.006 | 0.005 | 0.168 |
| 30A | 0.216                                | 0.093 | 0.106 | 0.057 | 0.086 | 0.051 | 0.002 | 0.001 | 0.03  | 0.026 | 0.006 | 0.005 | 0.222 |
| 30B | 0.229                                | 0.103 | NA    | NA    | NA    | NA    | 0.042 | 0.042 | 0.044 | 0.038 | NA    | NA    | 0.189 |
| 30C | NON-FILL OR TOO DISTORTED TO MEASURE |       |       |       |       |       |       |       |       |       |       |       |       |
| 31' | 0.39                                 | 0.15  | 0.008 | 0.005 | 0.362 | 0.214 | 0.012 | 0.012 | 0.008 | 0.006 | NA    | NA    | 0.195 |
| 31A | 0.337                                | 0.14  | 0.007 | 0.004 | 0.324 | 0.191 | 0.004 | 0.003 | 0.024 | 0.02  | 0.002 | 0.001 | 0.23  |
| 31B | 0.306                                | 0.136 | NA    | NA    | NA    | NA    | 0.09  | 0.089 | 0.138 | 0.118 | NA    | NA    | 0.176 |

## Raw Dimensional Data

|     |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 31C | 0.353 | 0.164 | NA    | NA    | NA    | NA    | 0.06  | 0.058 | 0.16  | 0.137 | NA    | NA    | 0.431 |
| 32' | 0.313 | 0.123 | 0.103 | 0.056 | 0.112 | 0.066 | 0.002 | 0.003 | 0.024 | 0.02  | 0.014 | 0.013 | 0.142 |
| 32A | 0.358 | 0.141 | 0.103 | 0.056 | 0.092 | 0.054 | 0.006 | 0.006 | 0.024 | 0.021 | 0.014 | 0.013 | 0.157 |
| 32B | 0.456 | 0.211 | NA    | NA    | NA    | NA    | 0.098 | 0.095 | 0.034 | 0.03  | NA    | NA    | 0.14  |
| 32C | 0.641 | 0.338 | NA    | NA    | NA    | NA    | 0.024 | 0.024 | 0.18  | 0.153 | NA    | NA    | 0.402 |
| 33' | 0.963 | 0.435 | 0.027 | 0.014 | 0.337 | 0.199 | 0.01  | 0.01  | 0.01  | 0.009 | 0.004 | 0.004 | 0.191 |
| 33A | 0.927 | 0.419 | 0.023 | 0.013 | 0.289 | 0.171 | 0.002 | 0.001 | 0.006 | 0.006 | 0.022 | 0.019 | 0.224 |
| 33B | 0.875 | 0.385 | NA    | NA    | NA    | NA    | 0.01  | 0.01  | 0.048 | 0.041 | NA    | NA    | 0.165 |
| 33C | 1.52  | 0.658 | NA    | NA    | NA    | NA    | 0.27  | 0.264 | 0.276 | 0.236 | NA    | NA    | 0.425 |
| 34' | 0.307 | 0.122 | 0.2   | 0.111 | 0.152 | 0.09  | 0.002 | 0.002 | 0.026 | 0.023 | 0.008 | 0.007 | 0.172 |
| 34A | 0.236 | 0.094 | 0.068 | 0.039 | 0.116 | 0.069 | 0.006 | 0.006 | 0.034 | 0.029 | 0.012 | 0.01  | 0.209 |
| 34B | 0.133 | 0.059 | NA    | NA    | NA    | NA    | 0.008 | 0.007 | 0.042 | 0.036 | NA    | NA    | 0.157 |
| 34C | 0.932 | 0.449 | NA    | NA    | NA    | NA    | 0.208 | 0.204 | 0.004 | 0.004 | NA    | NA    | 0.316 |
| 35' | 0.261 | 0.108 | 0.024 | 0.013 | 0.301 | 0.178 | NA    | 0.001 | 0.026 | 0.023 | 0.002 | 0.001 | 0.17  |
| 35A | 0.369 | 0.152 | 0.012 | 0.006 | 0.259 | 0.153 | 0.002 | 0.002 | 0.024 | 0.02  | 0.006 | 0.006 | 0.218 |
| 35B | 0.338 | 0.161 | NA    | NA    | NA    | NA    | 0.012 | 0.013 | 0.04  | 0.035 | NA    | NA    | 0.177 |
| 35C | 0.619 | 0.291 | 0.075 | 0.038 | 0.011 | 0.006 | 0.104 | 0.101 | 0.03  | 0.026 | 1.713 | 1.55  | 0.407 |
| 36' | 0.397 | 0.163 | 0.077 | 0.041 | 0.069 | 0.041 | NA    | NA    | 0.024 | 0.021 | 0.008 | 0.007 | 0.17  |
| 36A | 0.331 | 0.145 | 0.008 | 0.004 | 0.045 | 0.027 | 0.01  | 0.01  | 0.022 | 0.019 | 0.012 | 0.01  | 0.222 |
| 36B | 0.299 | 0.125 | NA    | NA    | NA    | NA    | 0.012 | 0.011 | 0.066 | 0.057 | NA    | NA    | 0.191 |
| 36C | 1.38  | 0.657 | NA    | NA    | NA    | NA    | 0.154 | 0.152 | 0.012 | 0.011 | NA    | NA    | 0.454 |

## **APPENDIX C**

### **Statistical Analysis of Casting Experiment**

Date: April 1, 1997  
 To: R. Owens  
 From: J. J. Wyckoff  
 Subject: Statistical Analysis Of Casting Experiment

The analysis of the data from the casting experiment indicated the following optimum settings of the casting parameters.

Table I. Optimum Settings

| <u>Parameter</u> | <u>Type A</u> | <u>Type B</u> | <u>Type C</u> |
|------------------|---------------|---------------|---------------|
| Gate Location    | Inner Rim     | Inner Rim     | Inner Rim     |
| Fixture          | Not Supported | Not Supported | Water         |
| Pour Temp        | 1700°C        | 1700°C        | 1500°C        |
| Mold Temp        | 875°C         | 1150°C        | 875°C         |
| Pour Speed       | 3 Seconds     | 3 Seconds     | 3 Seconds     |
| Cooling          | Insulated     | Insulated     | Fan           |
| Gate Operator    | -----         | -----         | -----         |
| Pour Operator    | -----         | -----         | -----         |
| No. of Gates     | Fewer         | More          | More          |
| Size of Gates    | -----         | -----         | -----         |

In the above table, Type A refers to failure modes: Non-Fill, Through Holes, Crack, and Cold Shut. Type B refers to failure modes: Dendritic Shrinkage, Gas Hole, Filament Shrinkage, and Shell Break. Type C refers to failure modes: Foreign Material, Surface Visual, and Surface Depression. Type A failure modes were considered the most critical, followed by Type B, and then by Type C.

There were no significant differences between gating operators, pour operators, or sizes of the gates. The optimum settings of the other parameters were determined by considering the statistical significance of the parameter, and its interactions, with any of the

other parameters. This was accomplished by using the SAS statistical package and its analysis of variance routines.

The table on the following page contains the number of occurrences of the three types of failure categories and their location. No data were available for serial numbers 1, 2, 17, and 27. The different locations are defined as follows,

- Location 1: Floor
- Location 2: Rim
- Location 3: Stronglink Pad
- Location 4: Cantilever Pad
- Location 5: Top of "T"
- Location 6: Side of "T" .

The next table contains the average number of occurrences for the three types of failure categories, by location.

Table II. Average Failure Mode Occurrences by Location

| <u>Location</u> | <u>Type A</u> | <u>Type B</u> | <u>Type C</u> |
|-----------------|---------------|---------------|---------------|
| Floor           | 3.2           | 0.8           | 0.3           |
| Rim             | 0.0           | 0.2           | 0.3           |
| Stronglink Pad  | 0.1           | 0.5           | 0.1           |
| Cantilever Pad  | 0             | 0.2           | 0.1           |
| Top of "T"      | 0.7           | 1.9           | 0.3           |
| Side of "T"     | 0.4           | 0.4           | 0.1           |

For the Type B failure modes, the highest average occurrence was 1.9, located at the top of the "T". However, the only casting parameter that had any statistically significant effect for these Type B failure modes at the top of the "T" was the number of gates. From Table I we note that the optimum setting for the number of gates was not consistent across the three different categories of failure modes. Since other casting parameters could be used to reduce the number of Type A failure modes, it is recommended that the number of gates be set to optimize the Type B and Type C failure modes, i.e. more. Otherwise, unless further investigation is taken, it is recommended that the casting parameters be fixed to the optimum settings for the Type A failure modes.

Table III. Number of Occurrences

| S/N | Location                |   |   |   |   |   |   |   |   |   |   |   |   |    |   |   |   |   |
|-----|-------------------------|---|---|---|---|---|---|---|---|---|---|---|---|----|---|---|---|---|
|     | 1                       |   |   | 2 |   |   | 3 |   |   | 4 |   |   | 5 |    |   | 6 |   |   |
|     | Failure Mode Categories |   |   |   |   |   |   |   |   |   |   |   |   |    |   |   |   |   |
|     | A                       | B | C | A | B | C | A | B | C | A | B | C | A | B  | C | A | B | C |
| 1   | -                       | - | - | - | - | - | - | - | - | - | - | - | - | -  | - | - | - | - |
| 2   | -                       | - | - | - | - | - | - | - | - | - | - | - | - | -  | - | - | - | - |
| 3   | 7                       | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 7  | 0 | 0 | 1 | 0 |
| 4   | 4                       | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1  | 0 | 1 | 1 | 0 |
| 5   | 1                       | 2 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1  | 0 | 0 | 0 | 0 |
| 6   | 0                       | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0  | 0 | 0 | 1 | 0 |
| 7   | 3                       | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1  | 0 | 1 | 1 | 0 |
| 8   | 3                       | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 3 | 1  | 0 | 2 | 0 | 0 |
| 9   | 3                       | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 0 | 0 | 1 | 0 |
| 10  | 6                       | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3  | 1 | 0 | 0 | 1 |
| 11  | 1                       | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0  | 0 | 1 | 0 | 0 |
| 12  | 2                       | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1  | 0 | 1 | 2 | 0 |
| 13  | 2                       | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 9  | 0 | 0 | 0 | 0 |
| 14  | 0                       | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1  | 0 | 0 | 2 | 0 |
| 15  | 2                       | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 2  | 1 | 0 | 0 | 0 |
| 16  | 0                       | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 2  | 1 | 0 | 0 | 0 |
| 17  | -                       | - | - | - | - | - | - | - | - | - | - | - | - | -  | - | - | - | - |
| 18  | 8                       | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 1  | 0 | 1 | 0 | 0 |
| 19  | 13                      | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 3  | 0 | 0 | 1 | 0 |
| 20  | 10                      | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0  | 0 | 1 | 0 | 0 |
| 21  | 2                       | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0  | 1 | 0 | 0 | 0 |
| 22  | 0                       | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0  | 1 | 0 | 0 | 0 |
| 23  | 0                       | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0  | 1 | 0 | 0 | 0 |
| 24  | 1                       | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 3  | 1 | 0 | 1 | 0 |
| 25  | 1                       | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0  | 1 | 0 | 0 | 1 |
| 26  | 3                       | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1  | 1 | 0 | 0 | 0 |
| 27  | -                       | - | - | - | - | - | - | - | - | - | - | - | - | -  | - | - | - | - |
| 28  | 3                       | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 14 | 0 | 1 | 0 | 0 |
| 29  | 6                       | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1  | 0 | 0 | 1 | 0 |
| 30  | 2                       | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1  | 0 | 0 | 0 | 0 |
| 31  | 4                       | 2 | 7 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1  | 0 | 1 | 0 | 0 |
| 32  | 2                       | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0  | 0 | 1 | 0 | 0 |
| 33  | 7                       | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0  | 0 | 1 | 0 | 0 |
| 34  | 5                       | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3  | 0 | 0 | 0 | 0 |
| 35  | 0                       | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4  | 1 | 0 | 0 | 0 |
| 36  | 0                       | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0  | 0 | 0 | 0 | 0 |

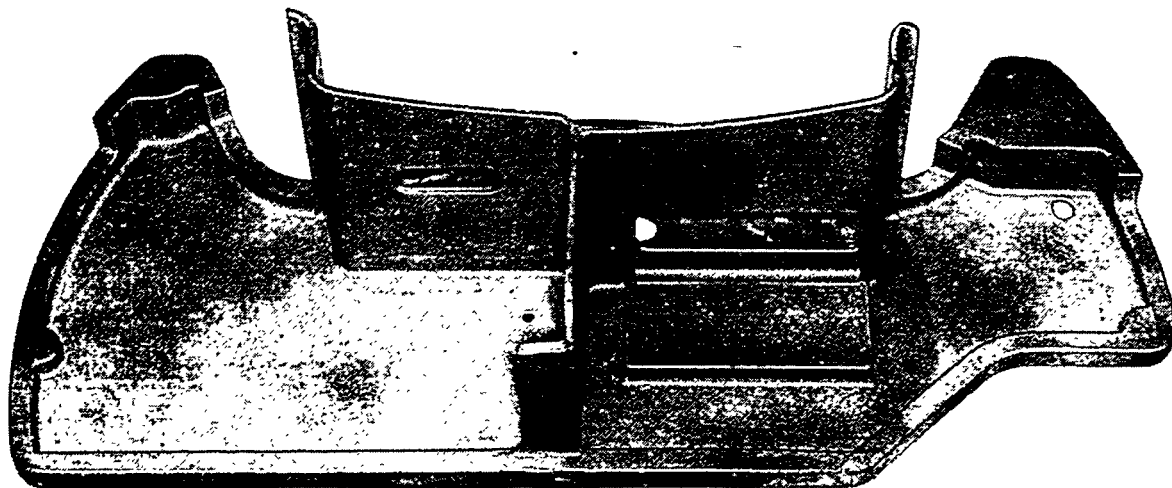
**R. Owens**  
**Page 4**

If you have any questions, please call me.

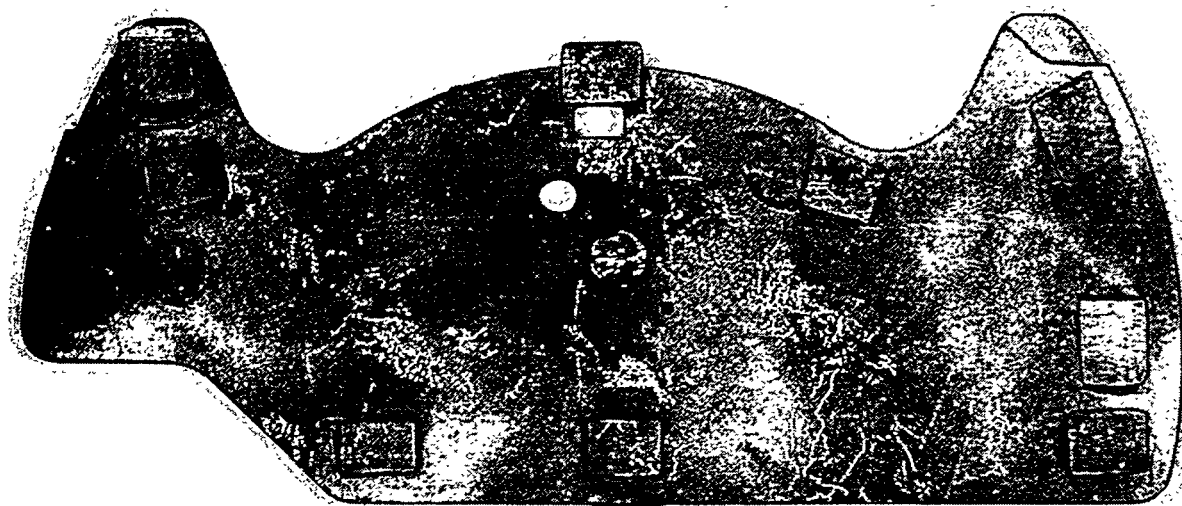
*James Wyckoff*

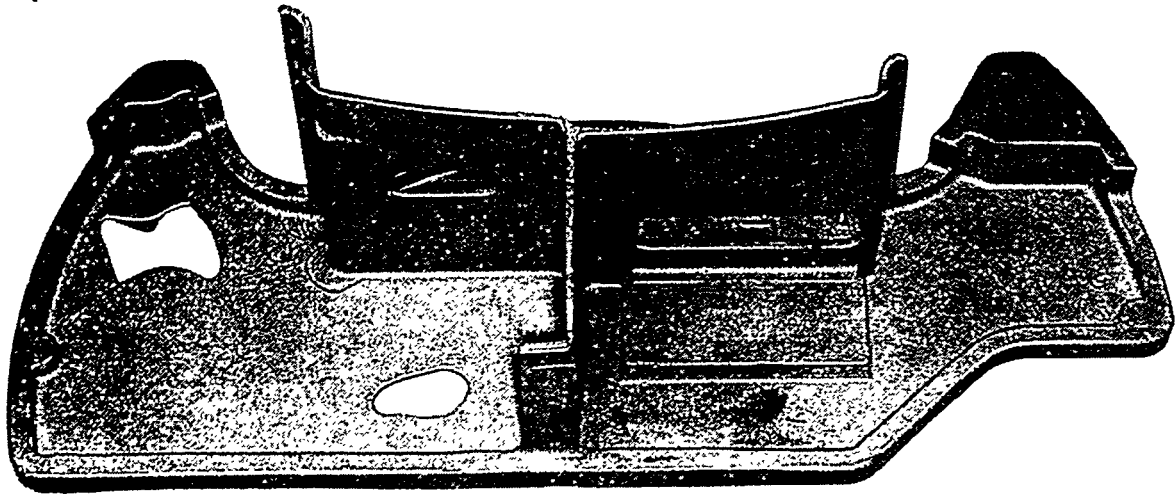
## **APPENDIX D**

### **Photographs of Final Castings**

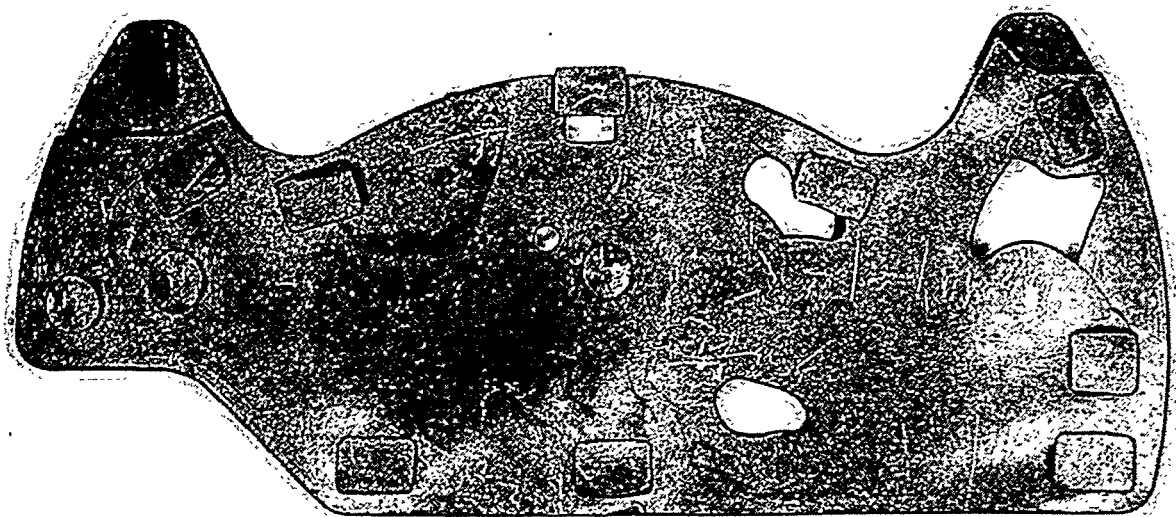


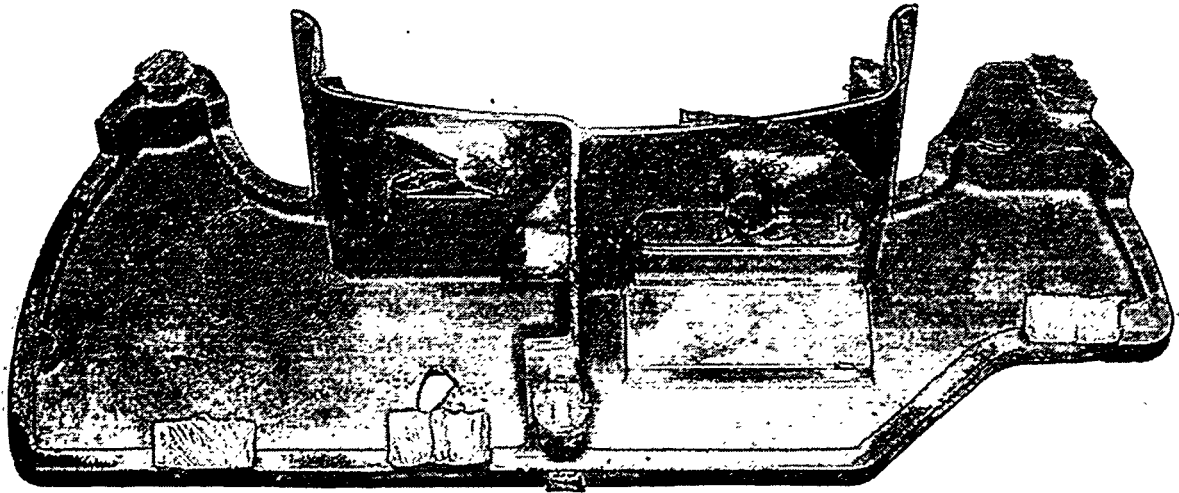
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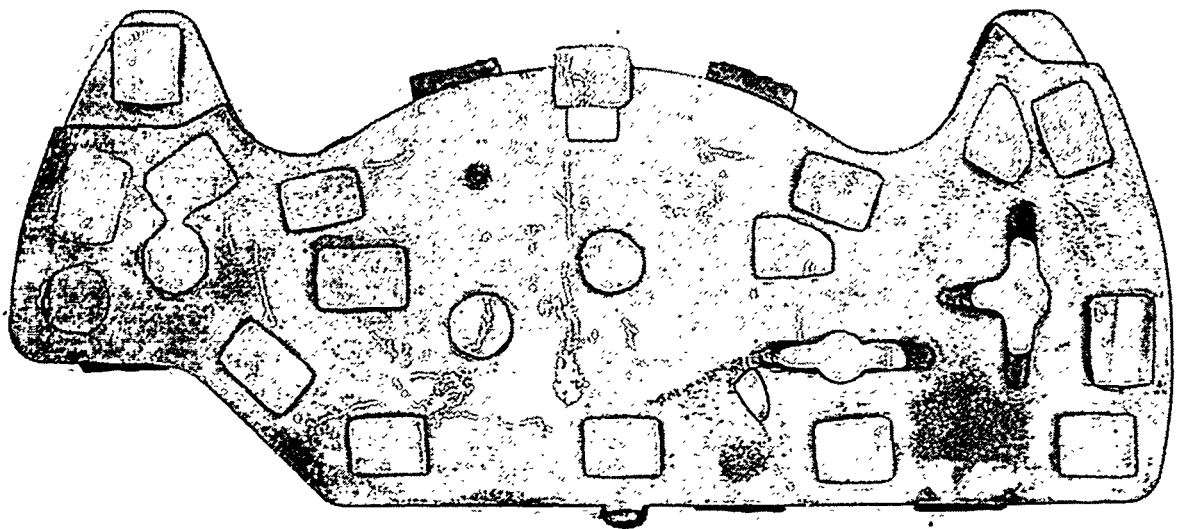


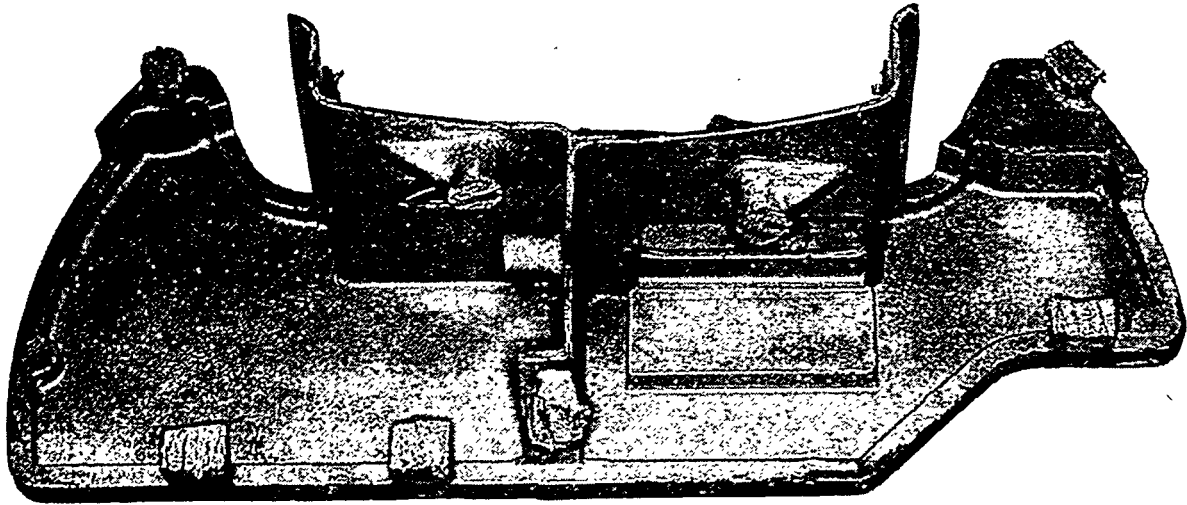
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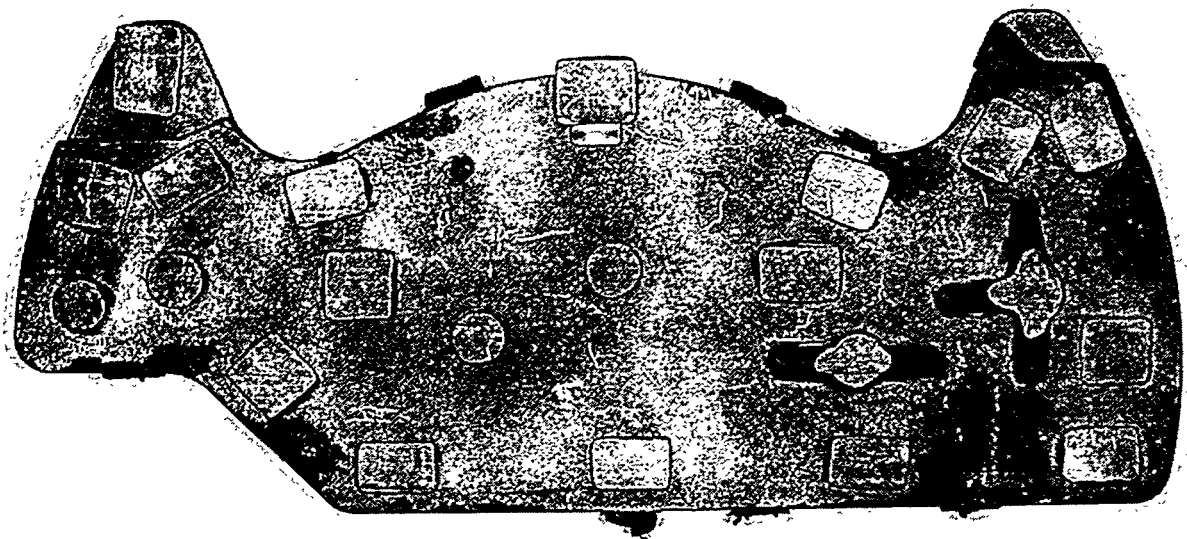


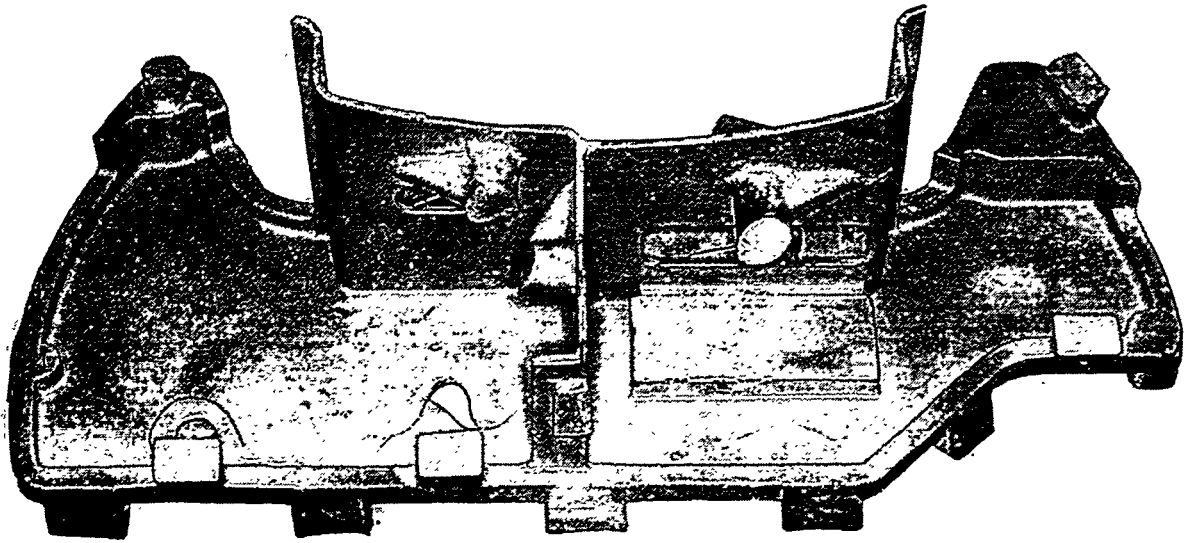
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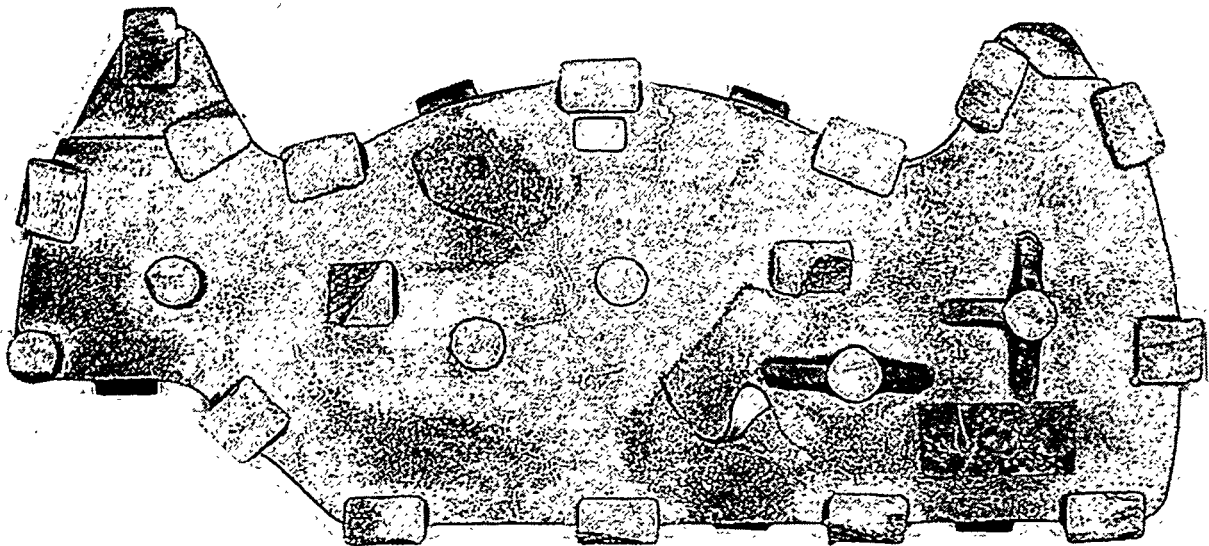


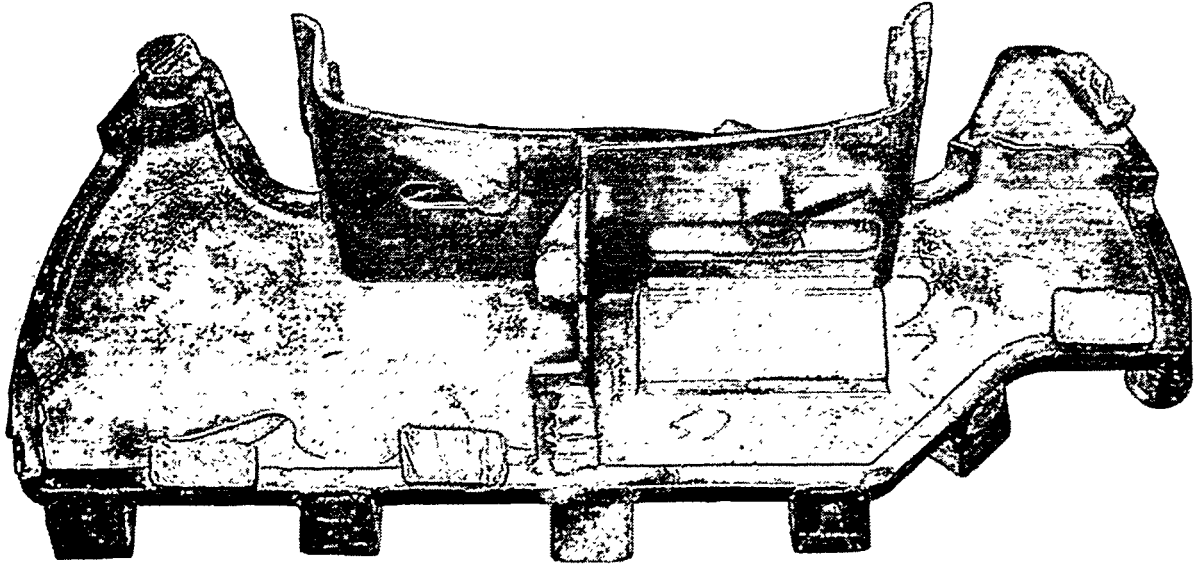
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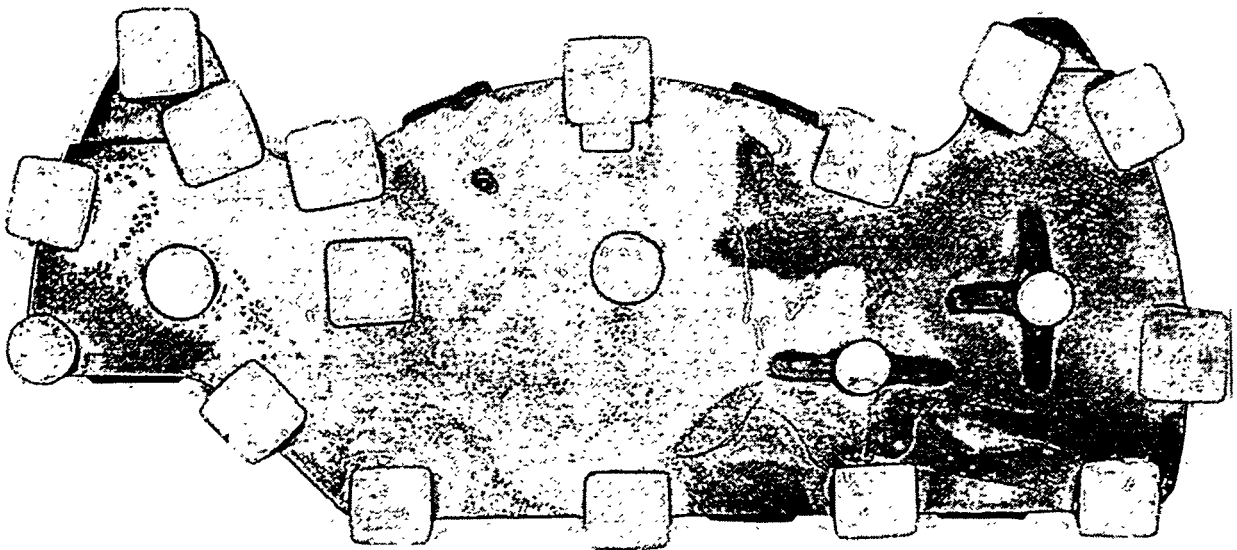


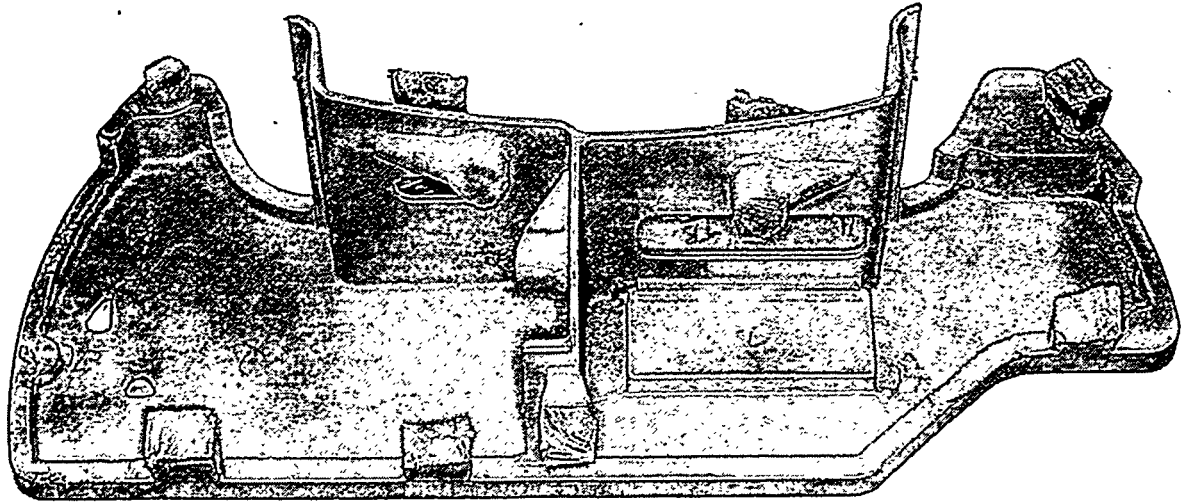
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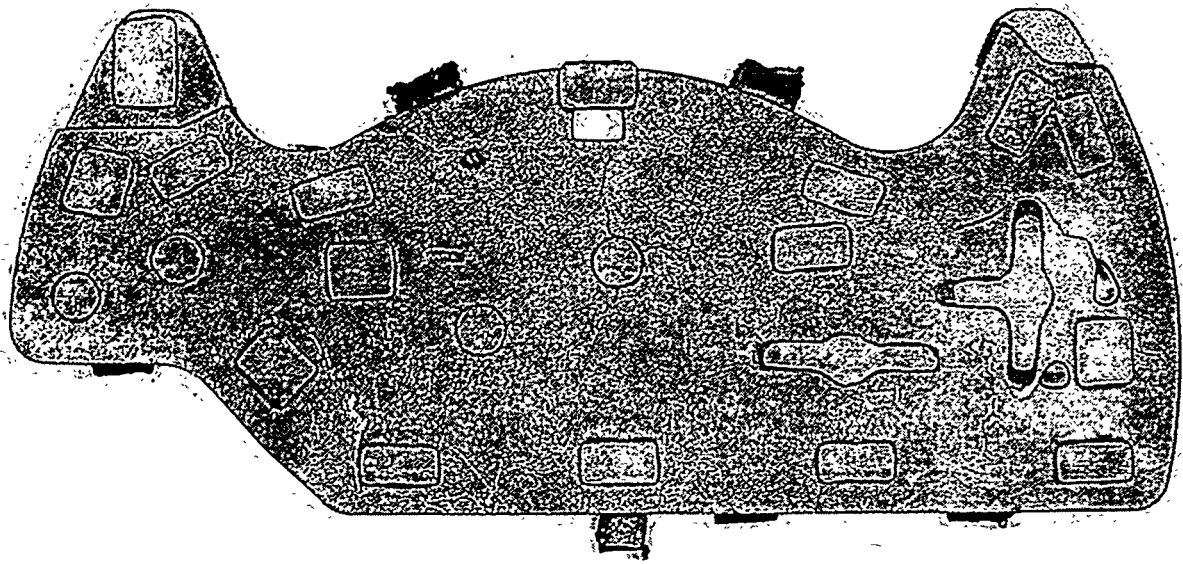


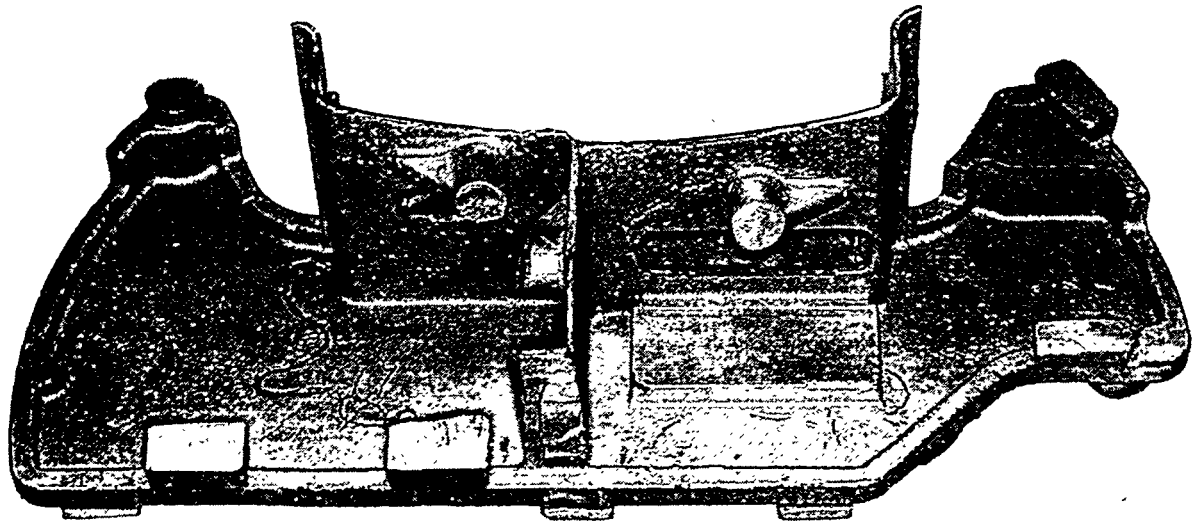
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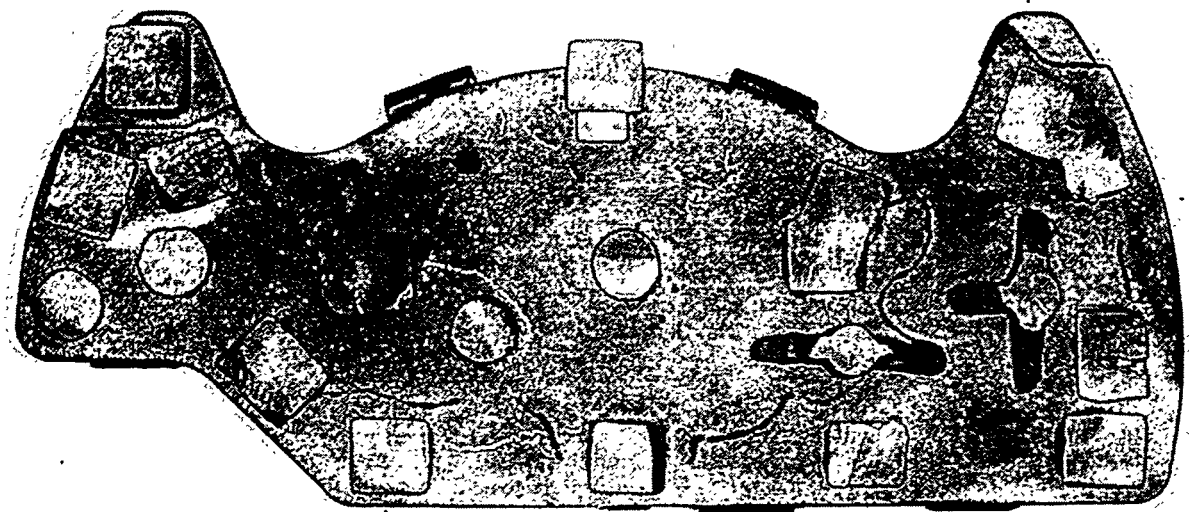


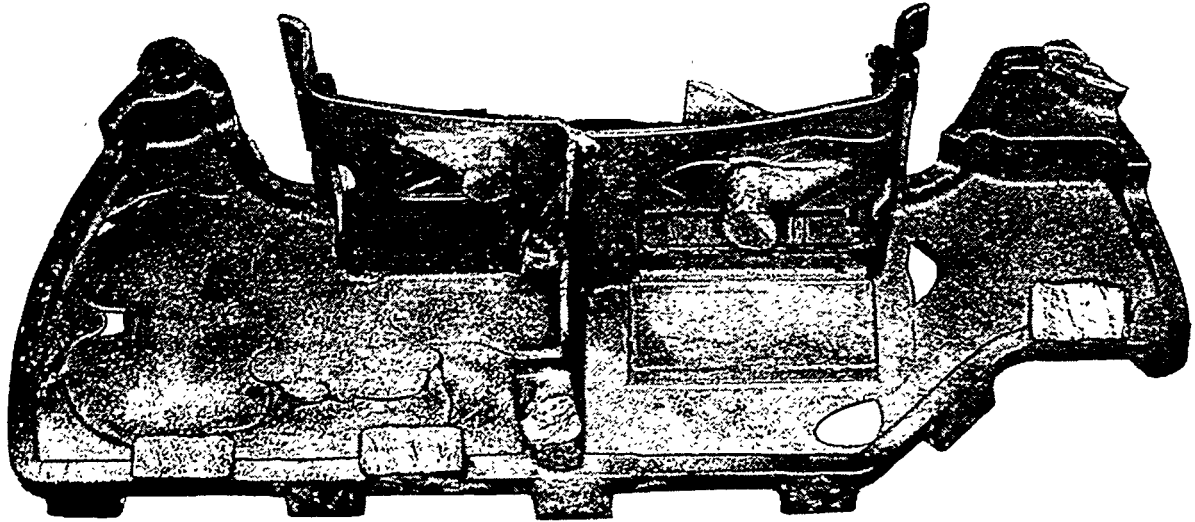
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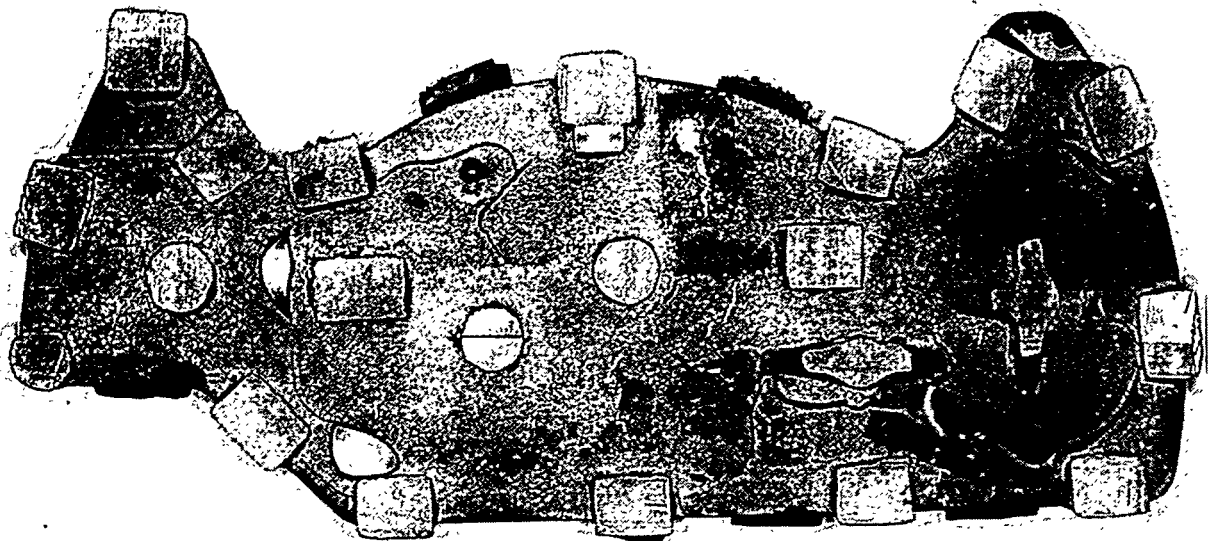


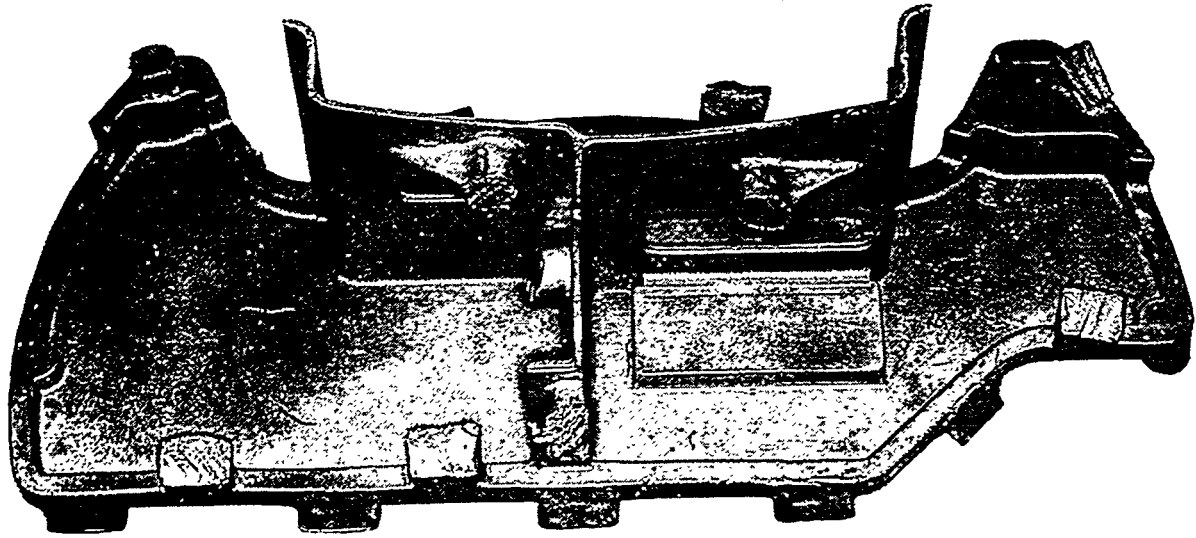
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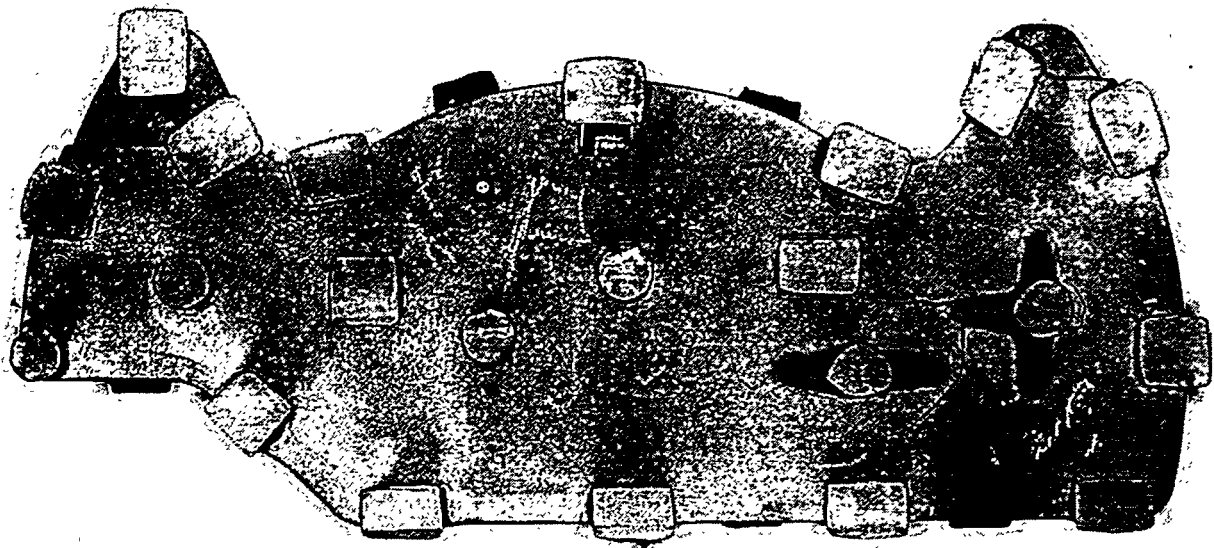


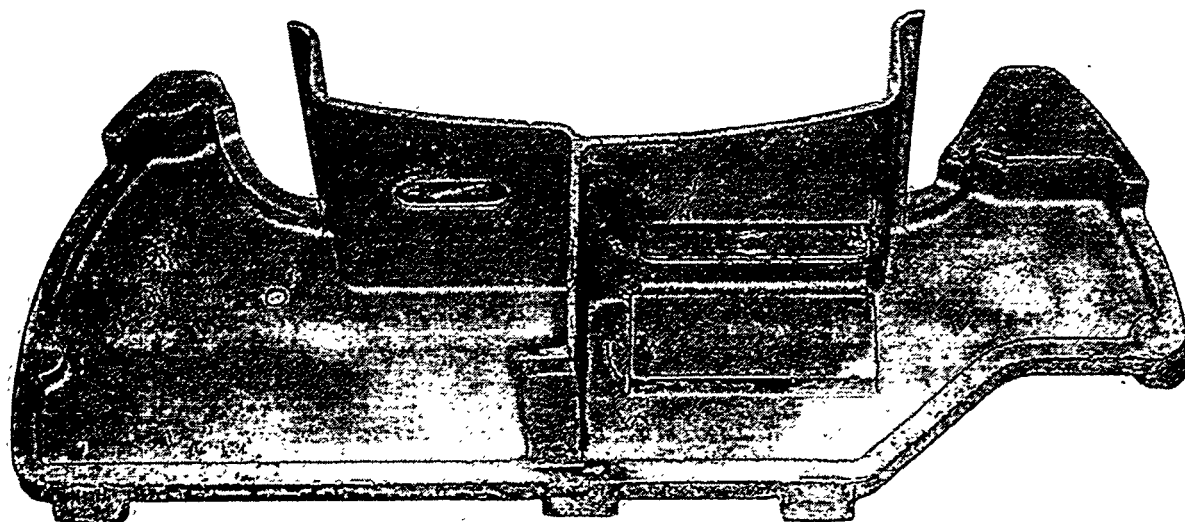
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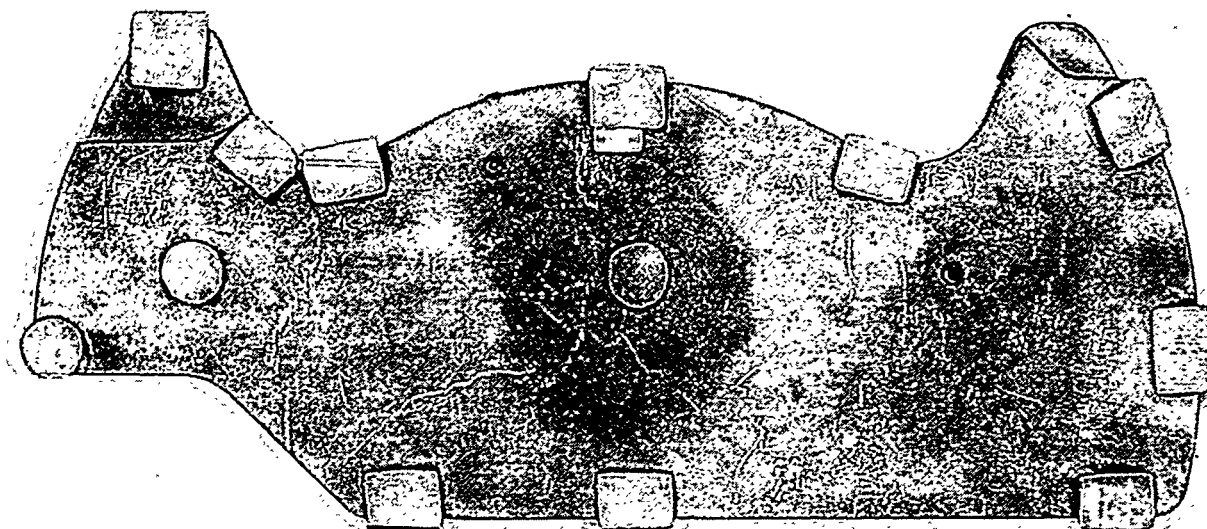


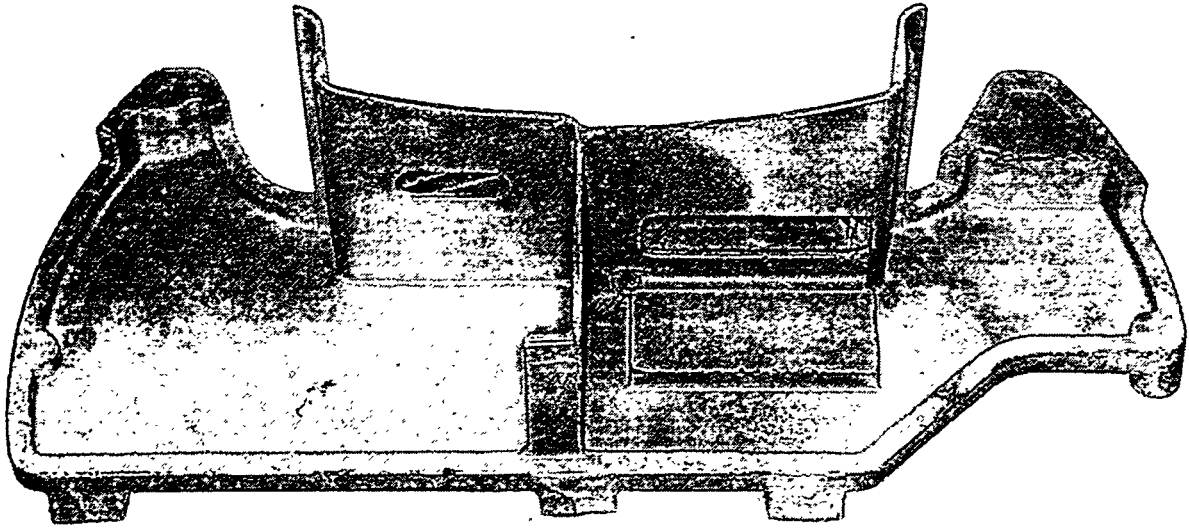
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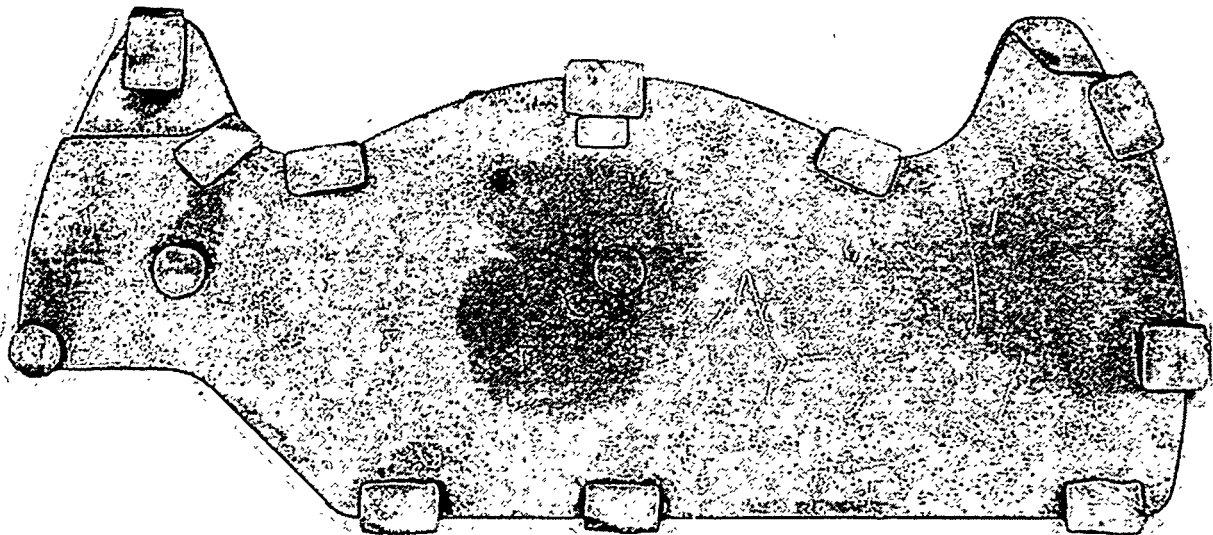


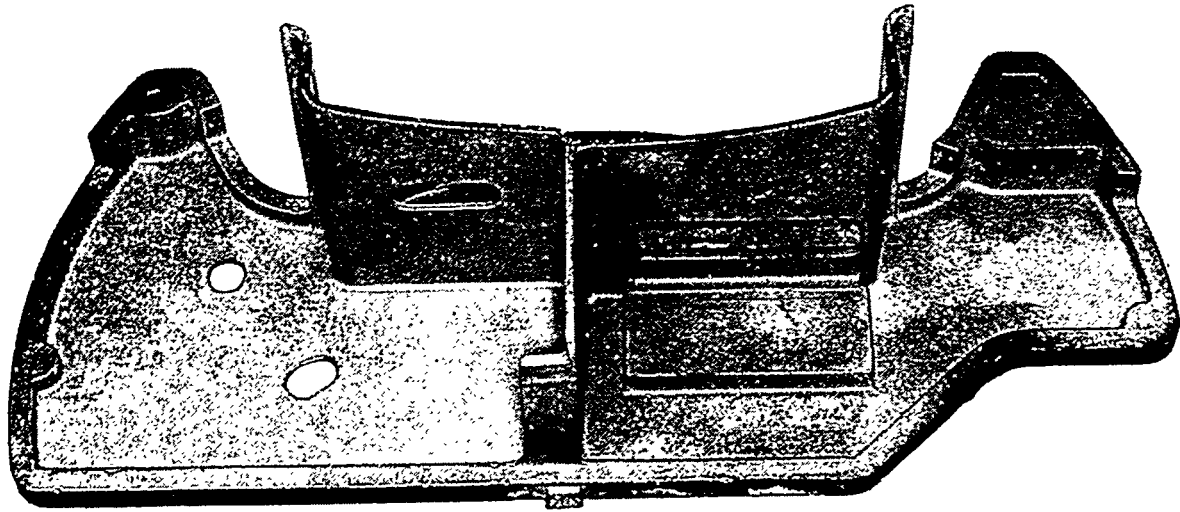
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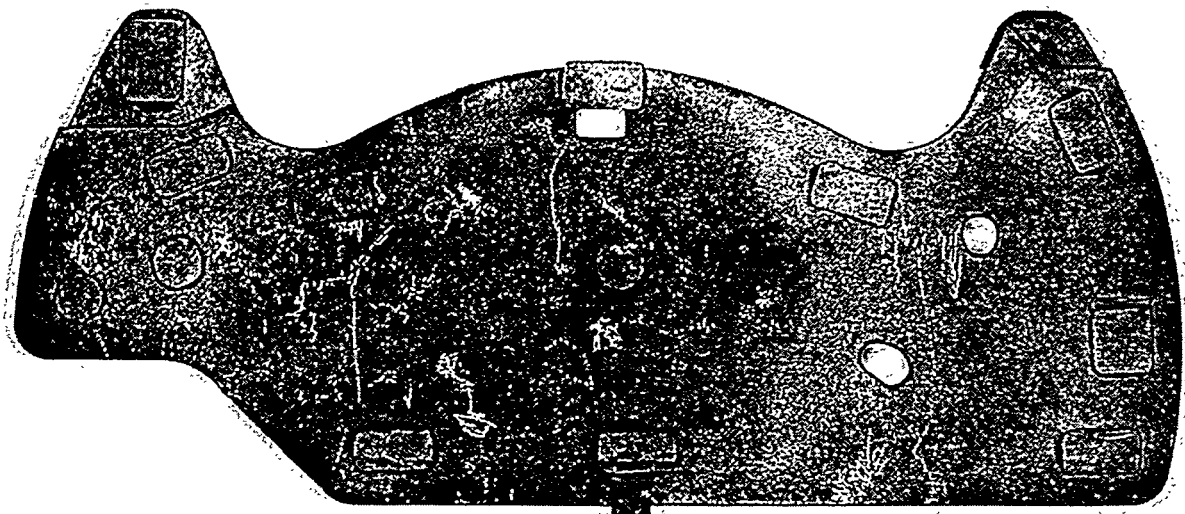


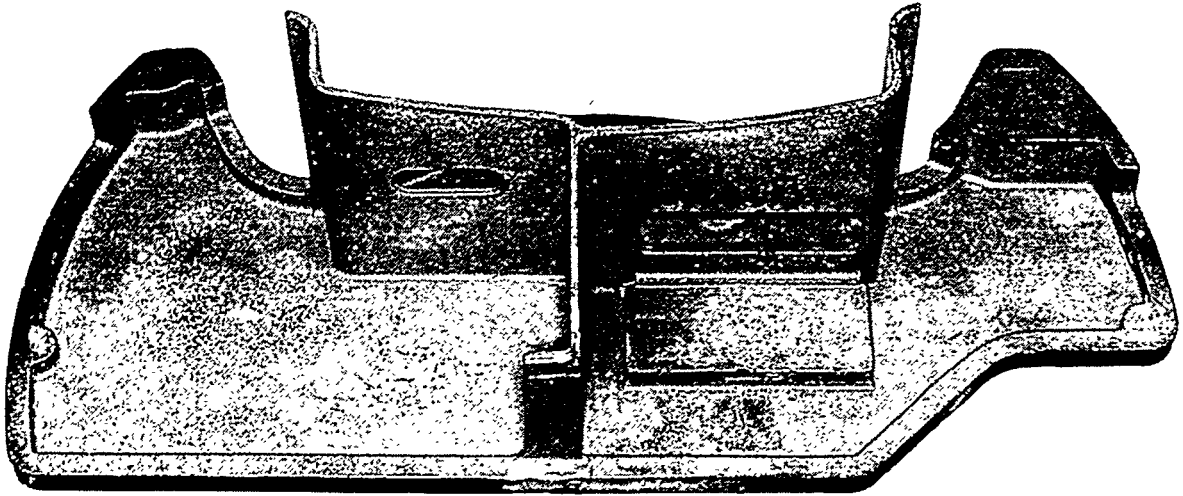
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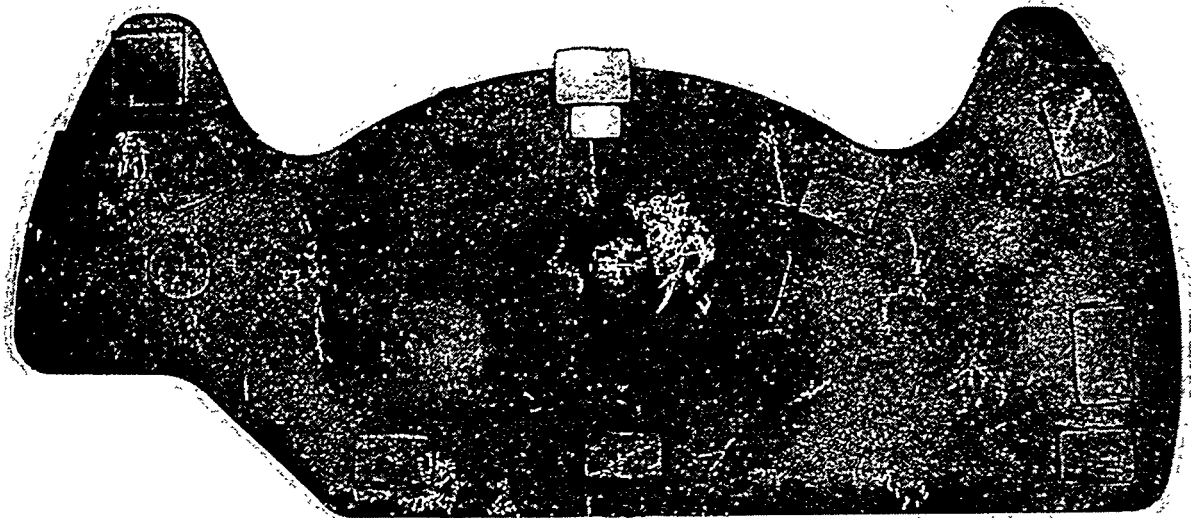


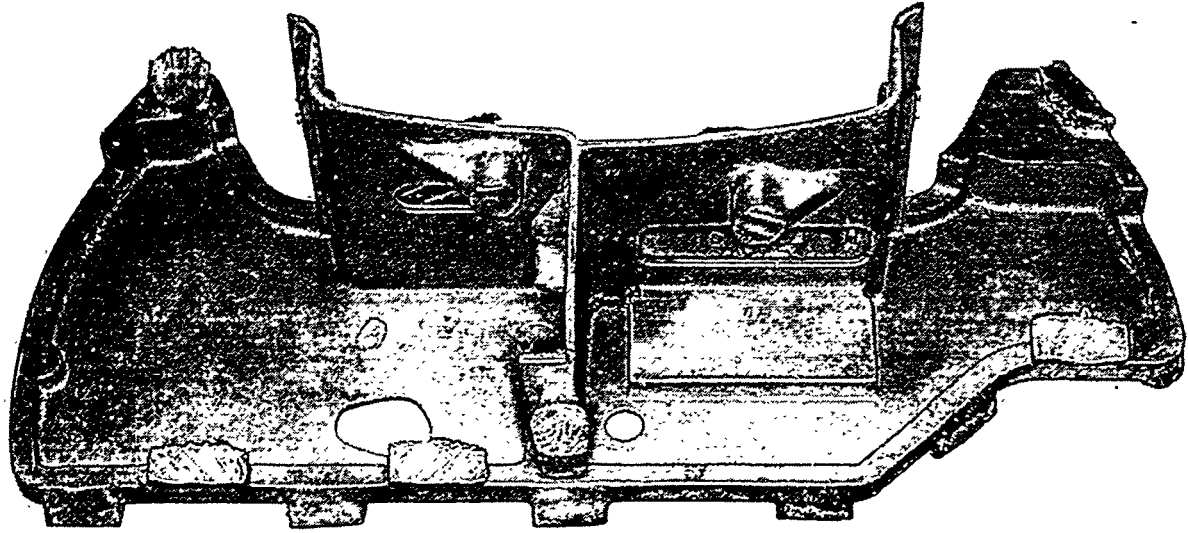
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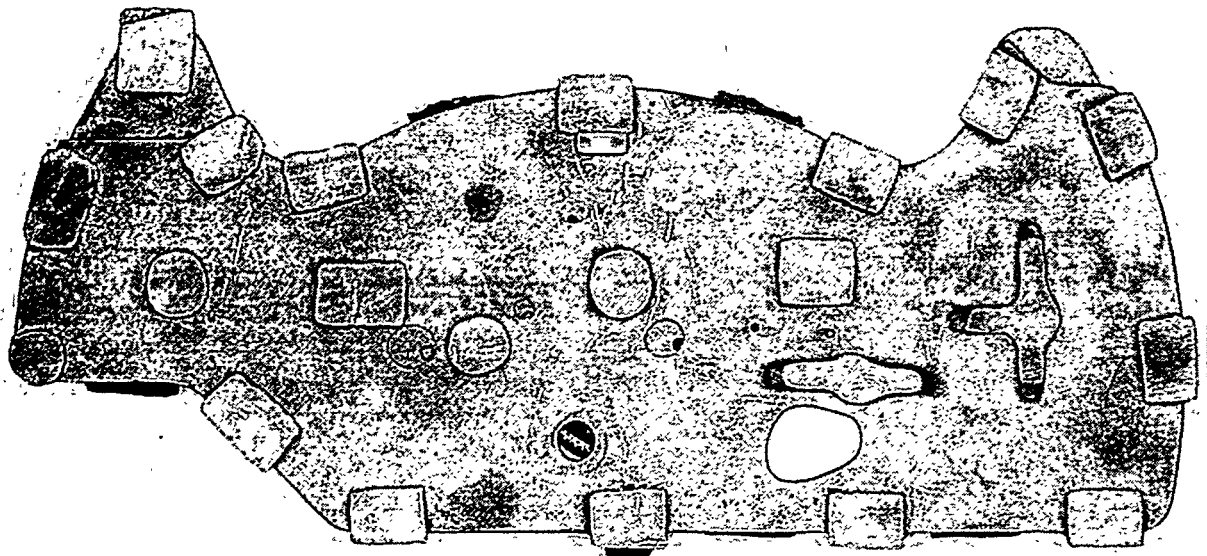


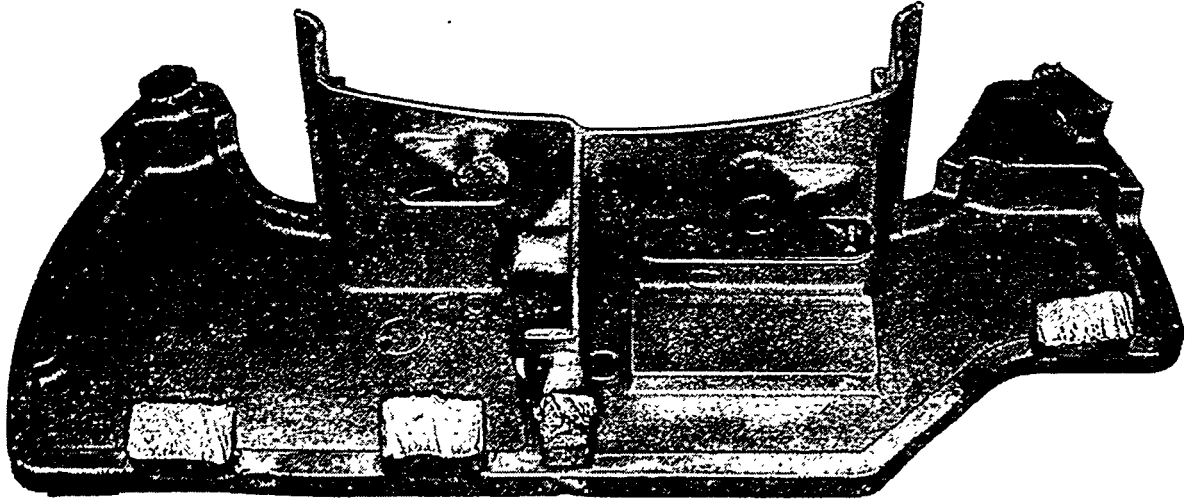
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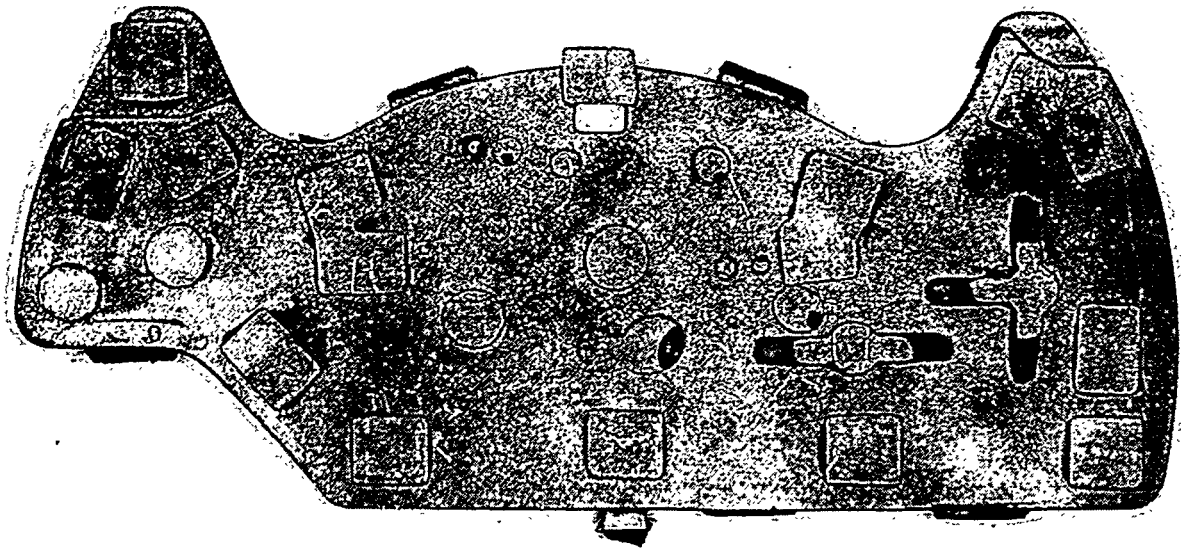


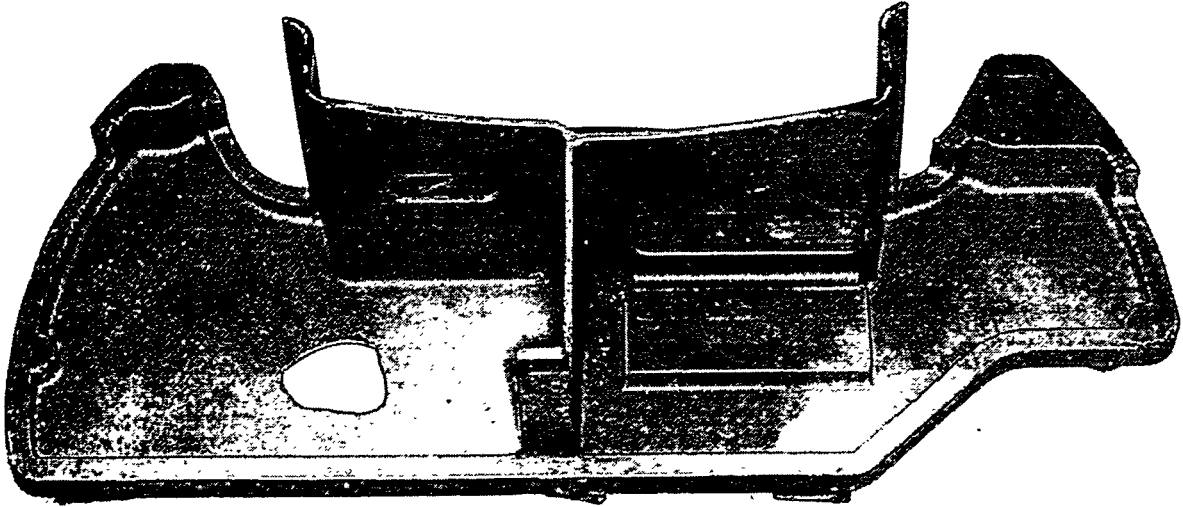
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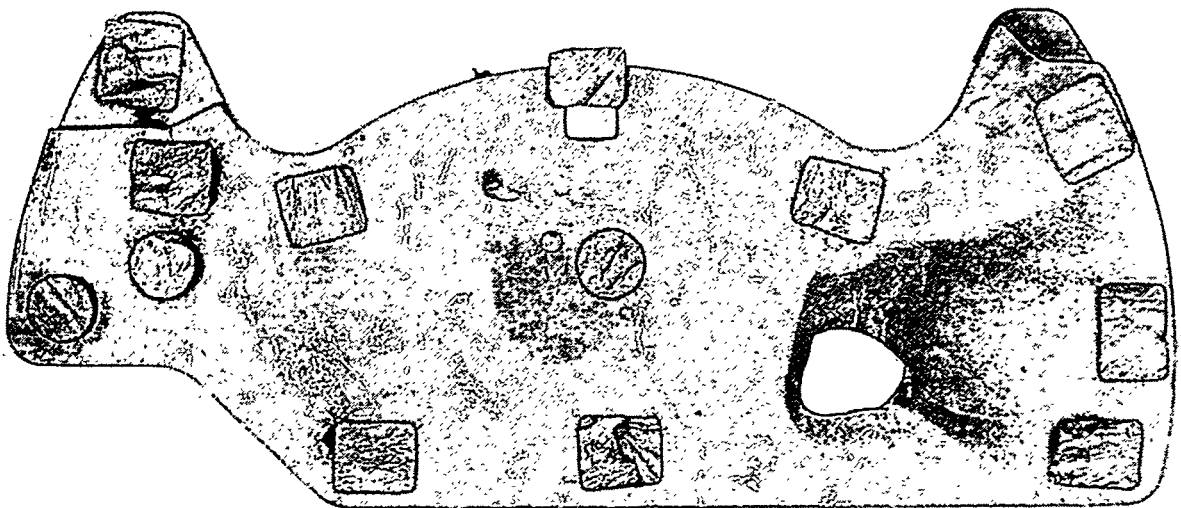


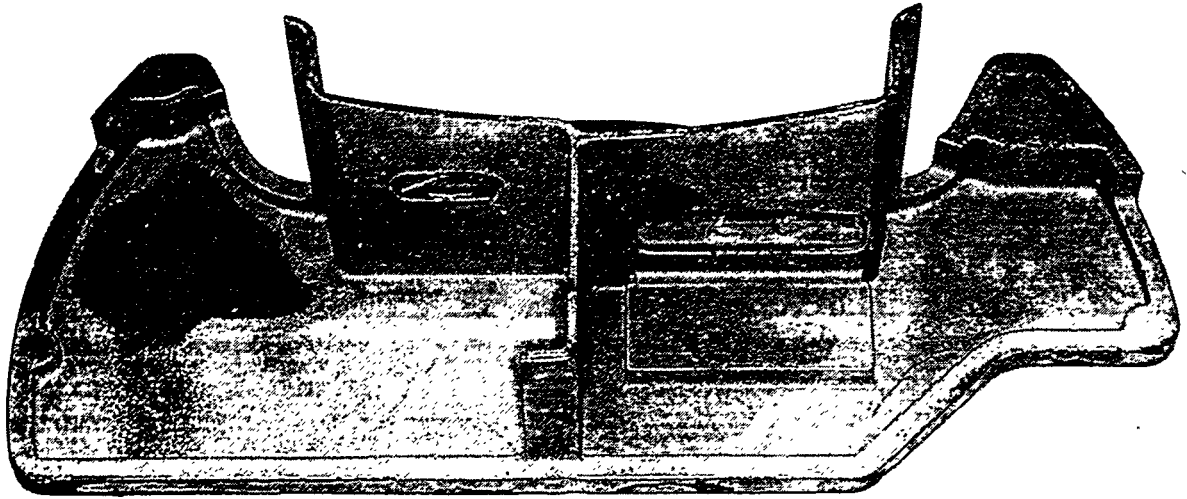
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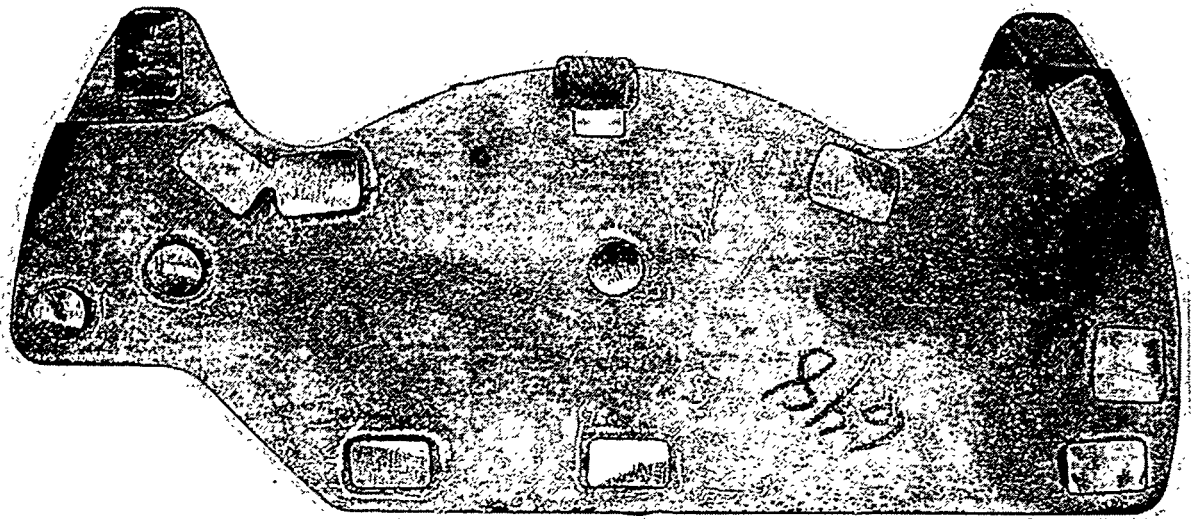


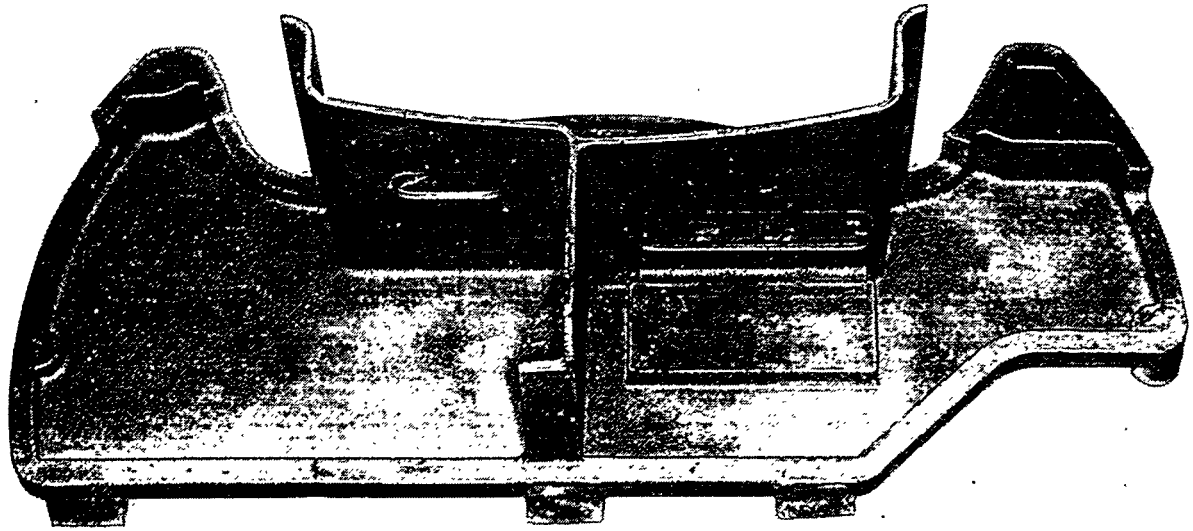
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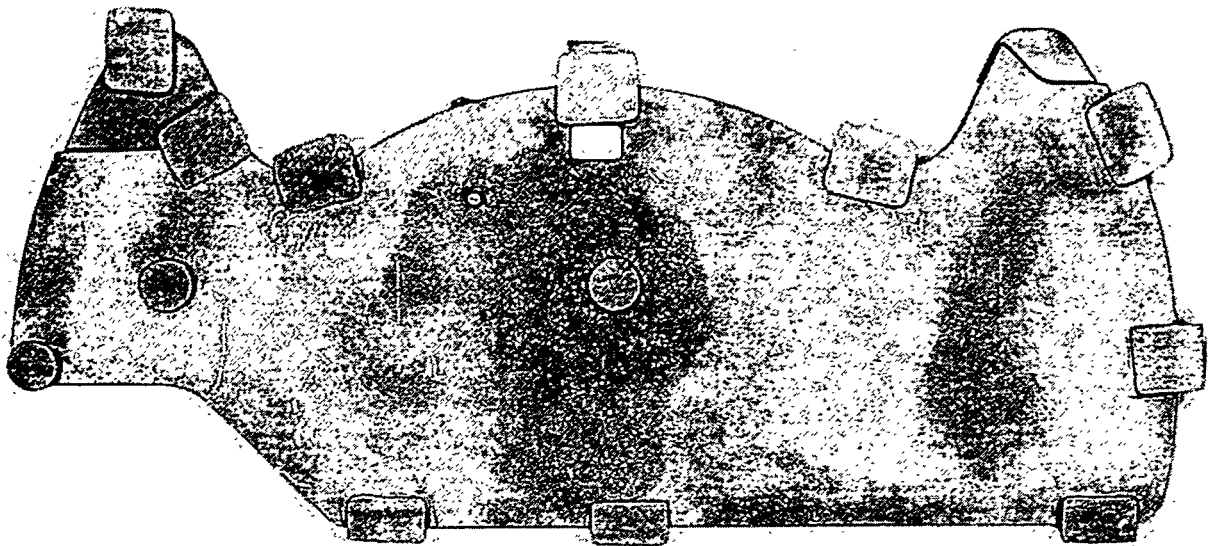


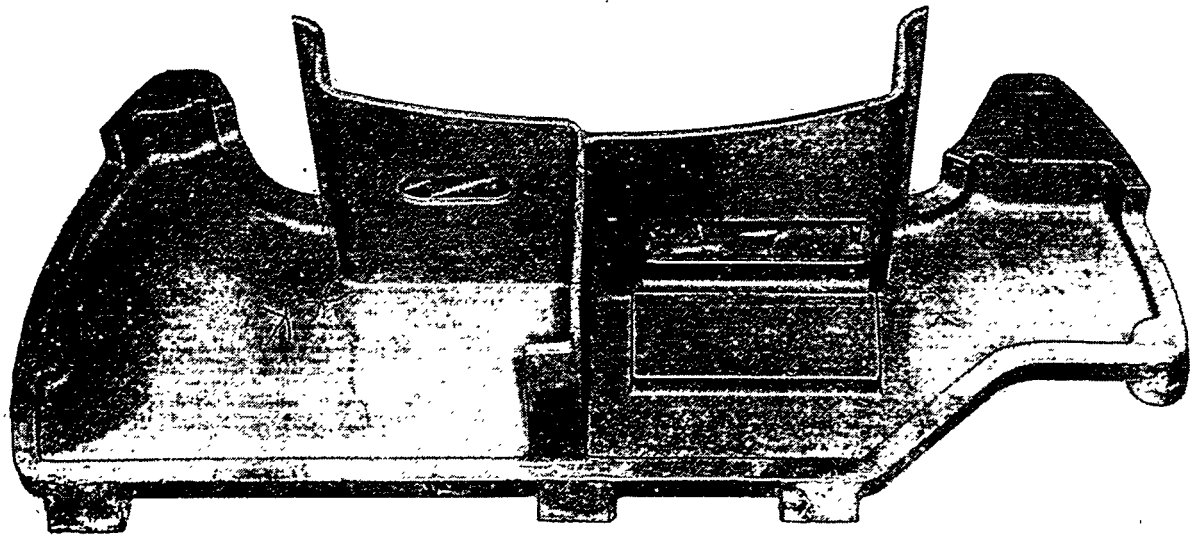
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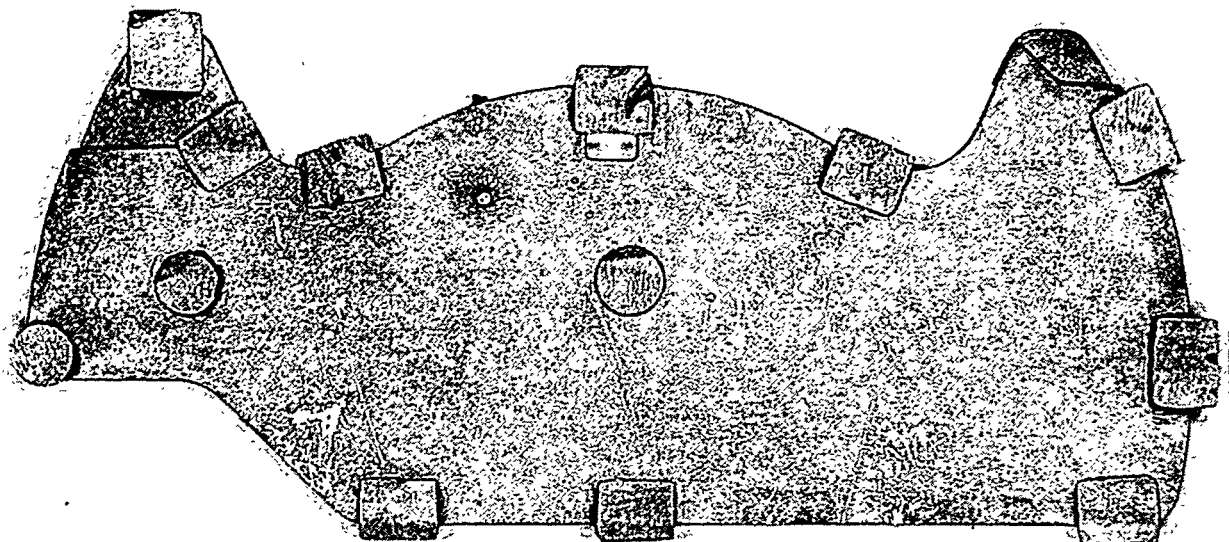


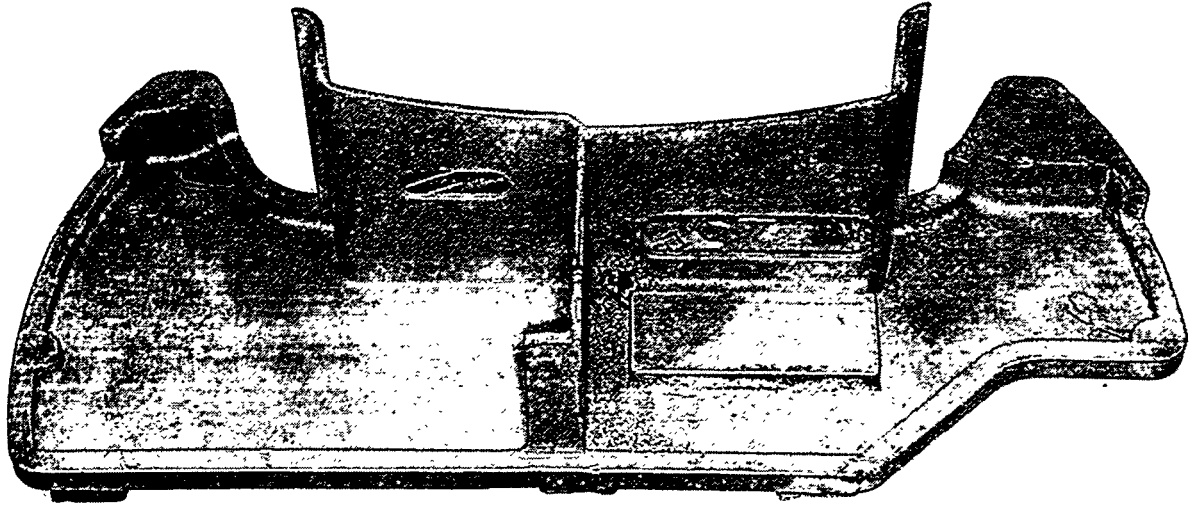
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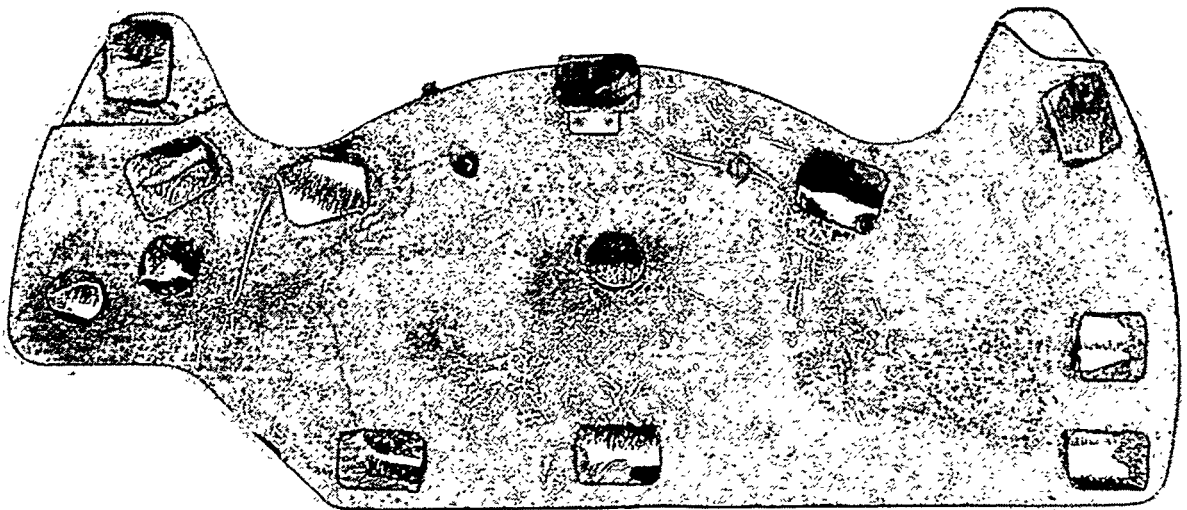


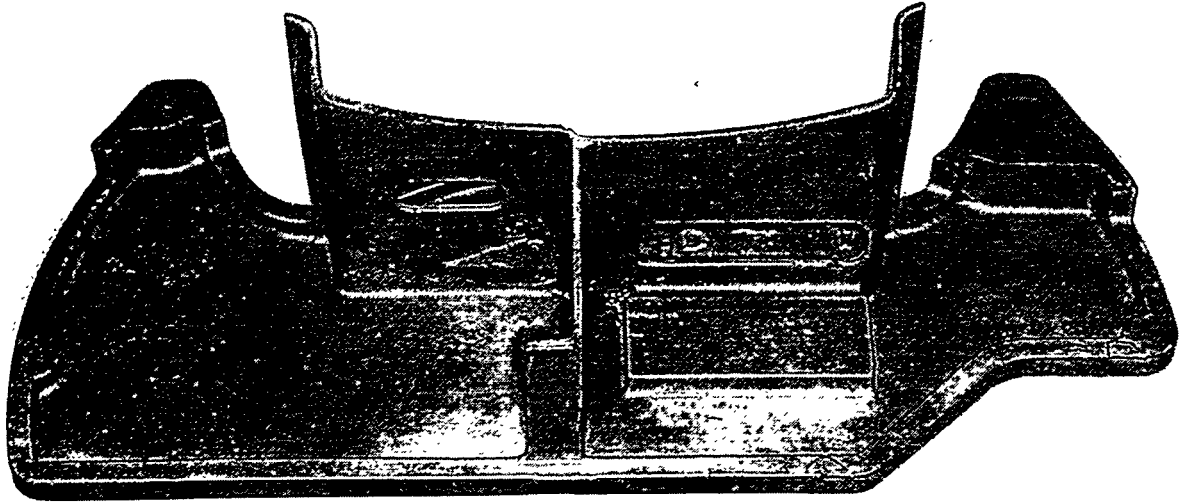
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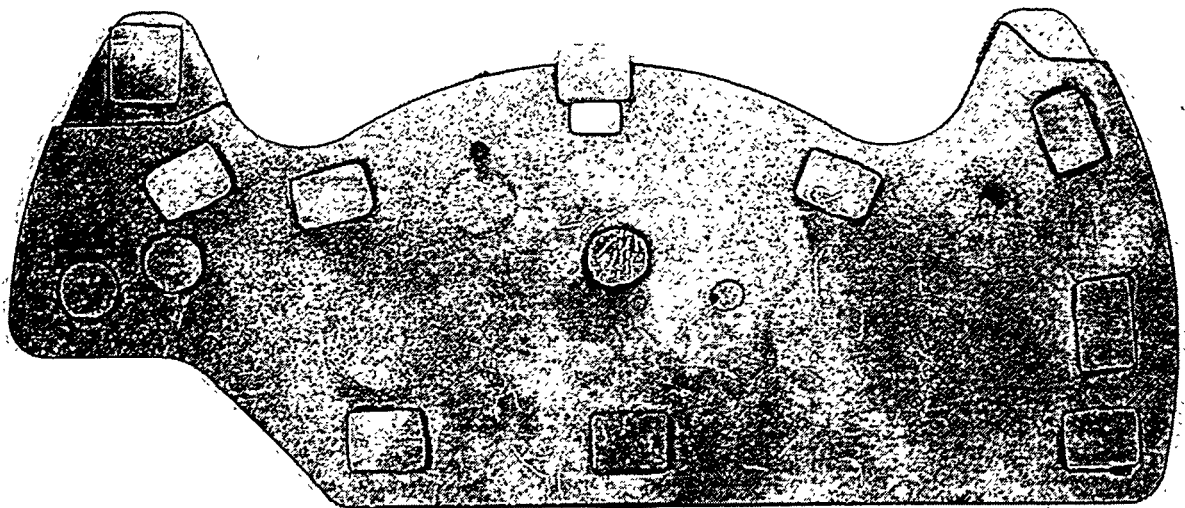


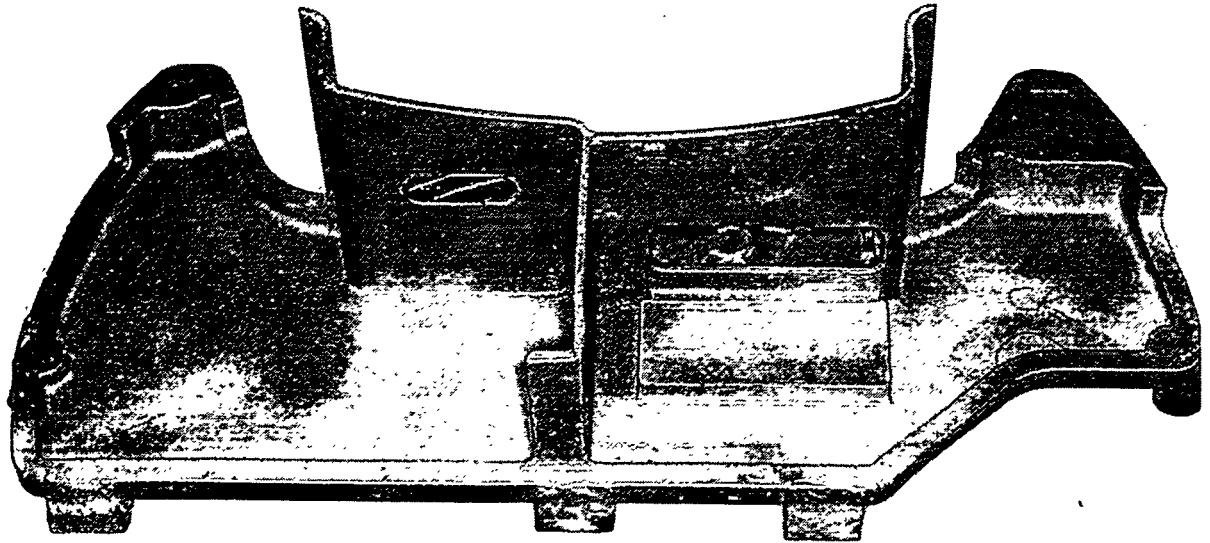
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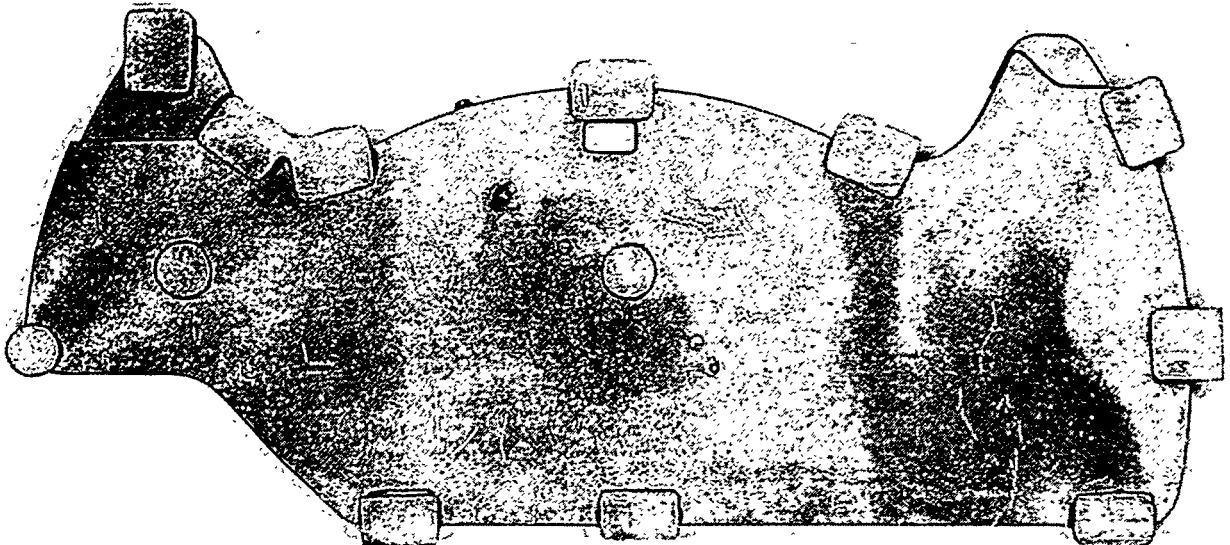


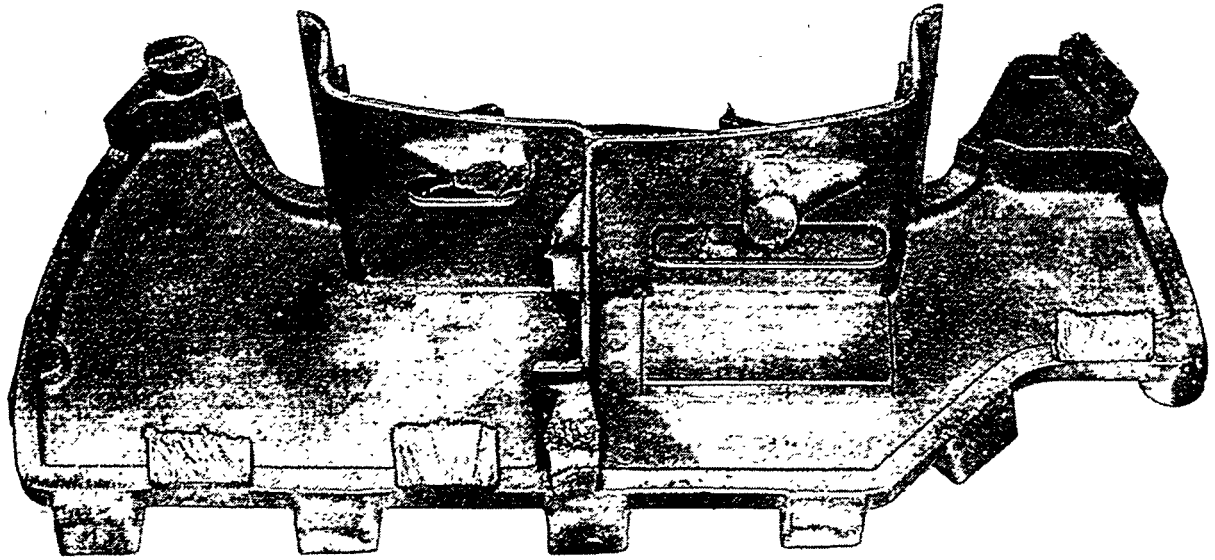
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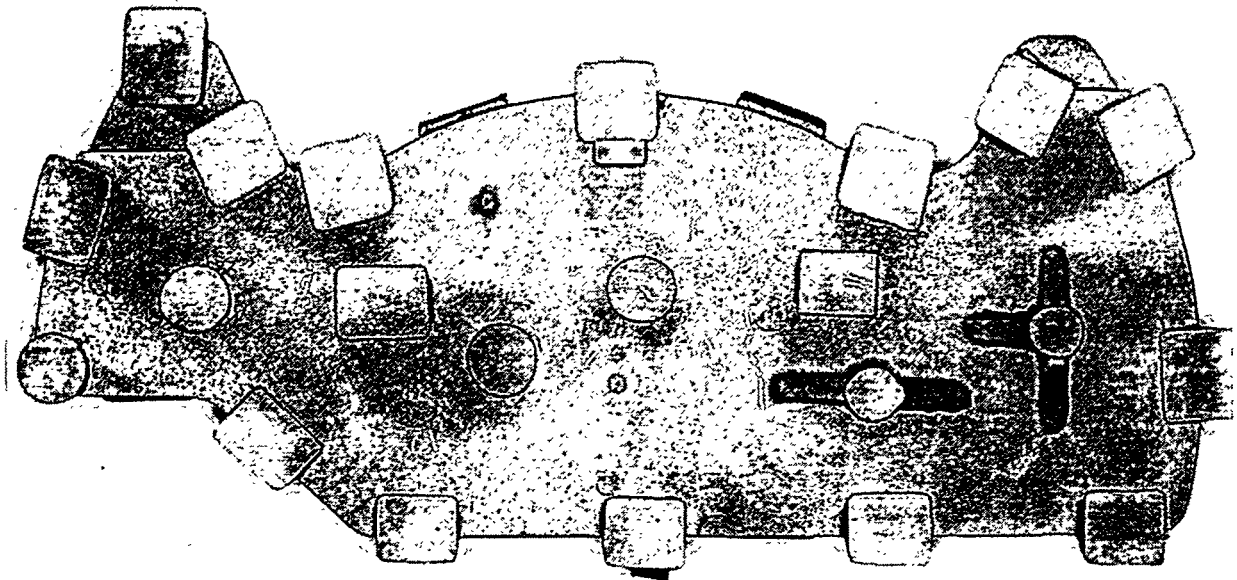


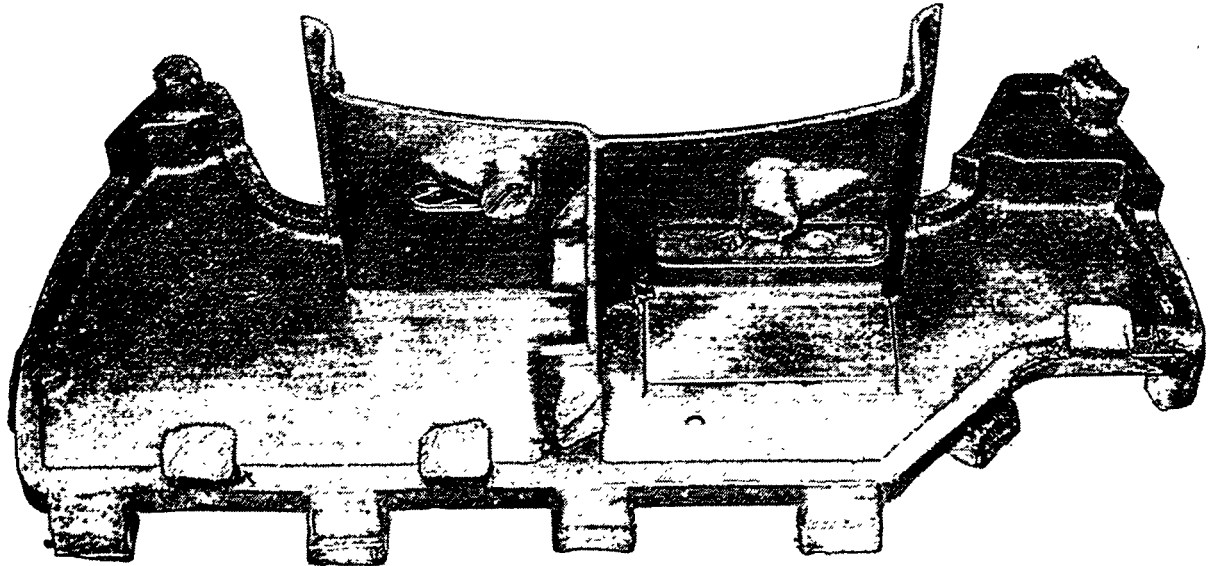
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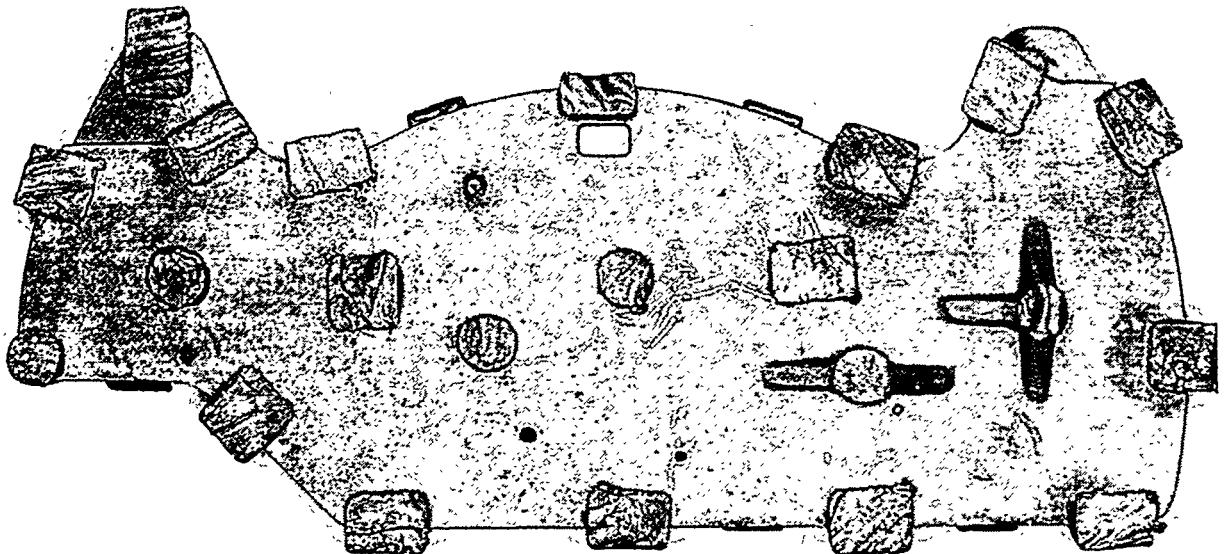


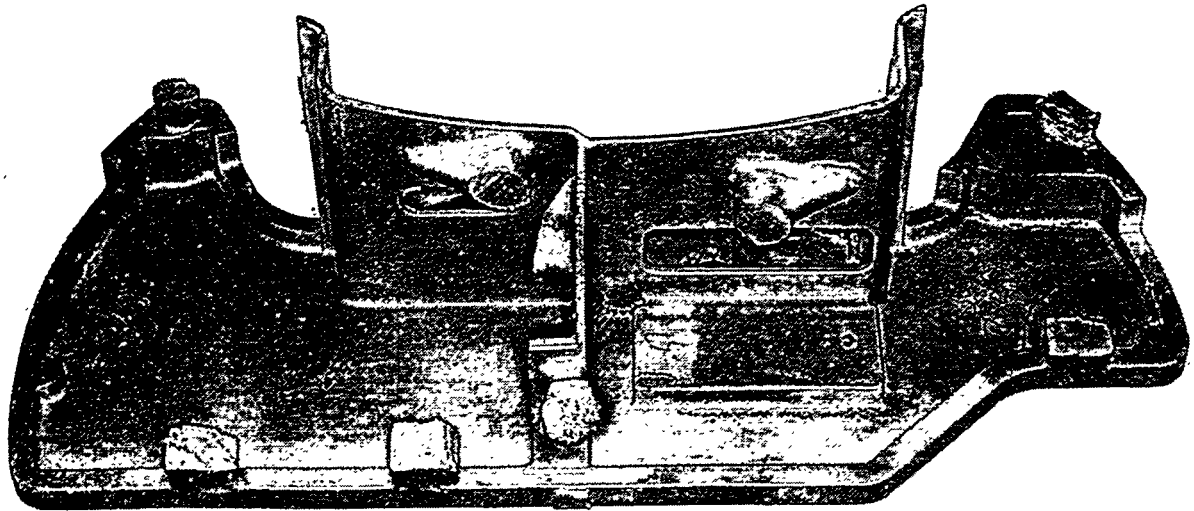
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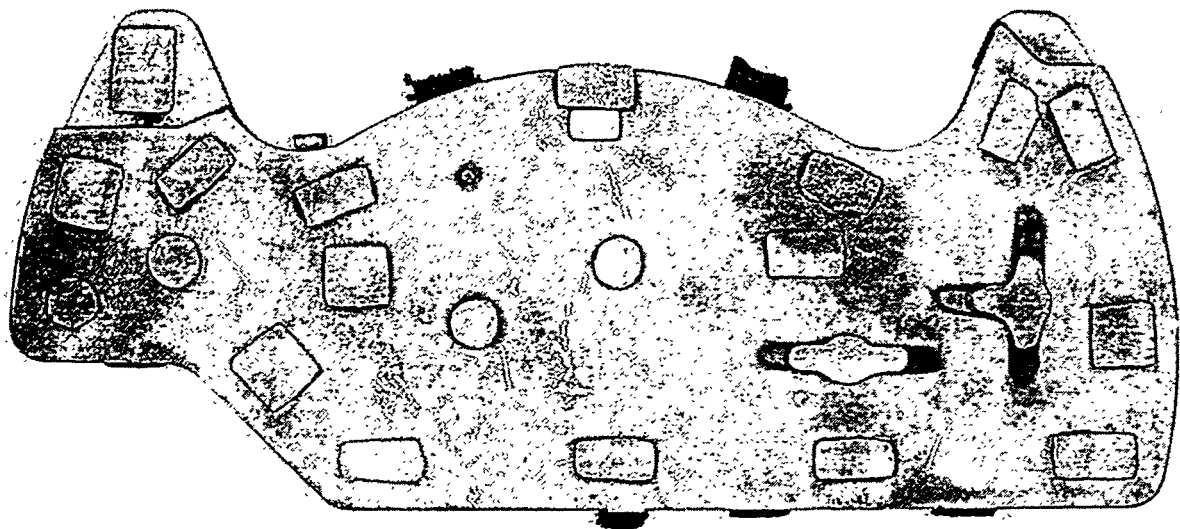


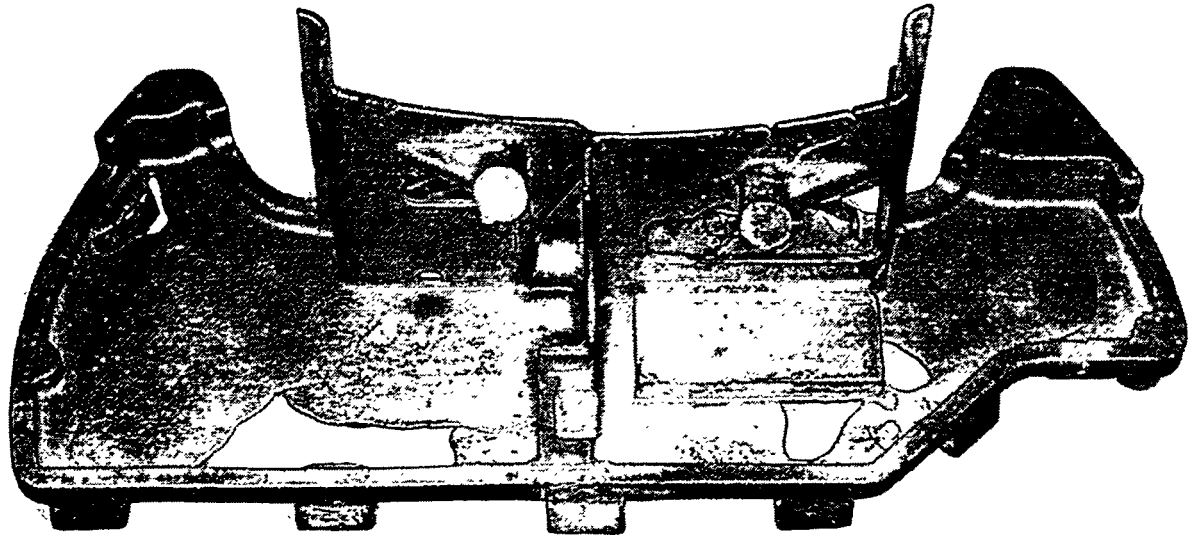
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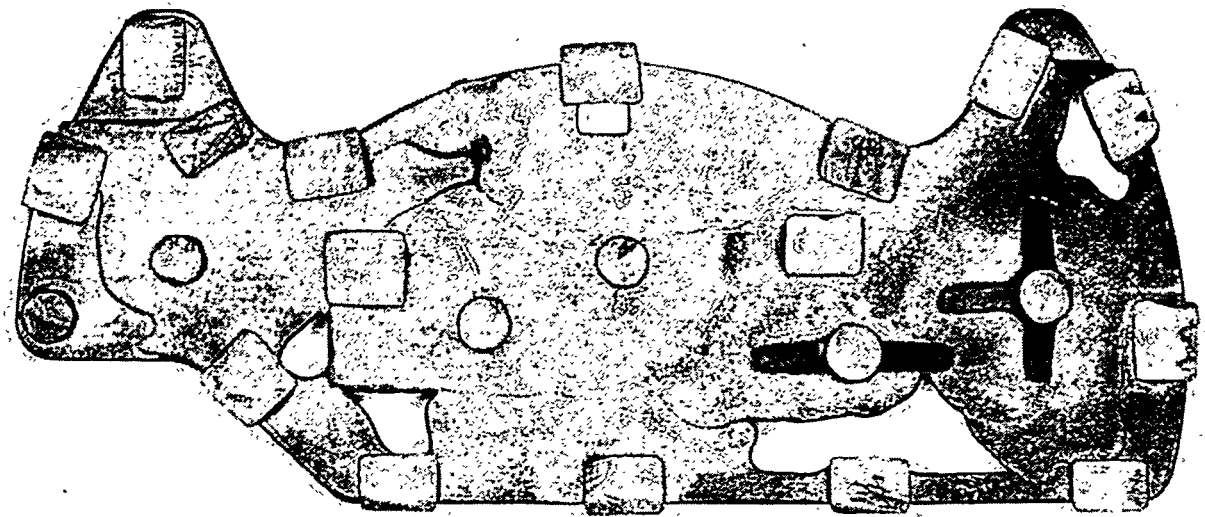


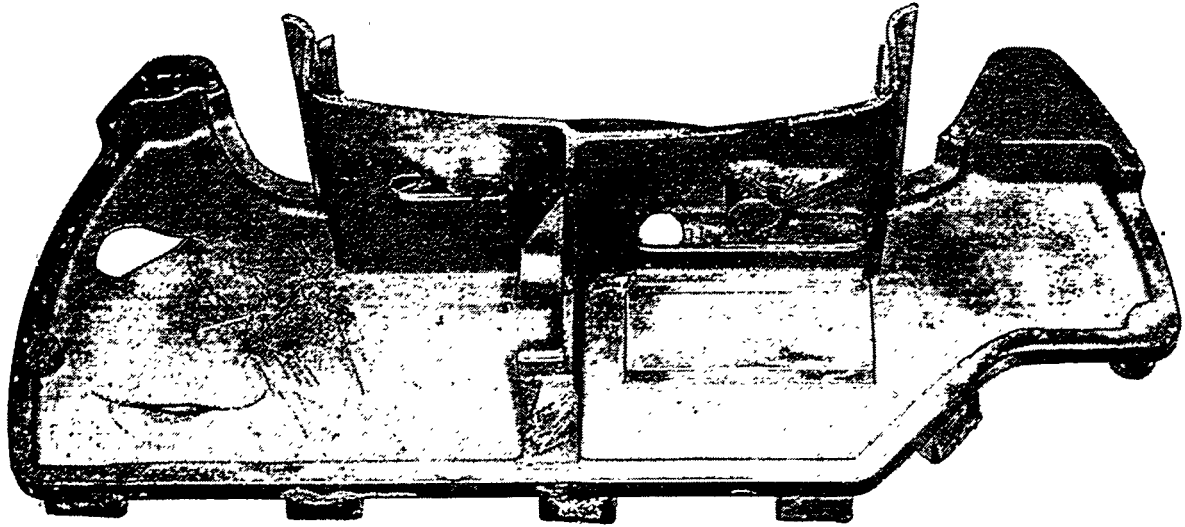
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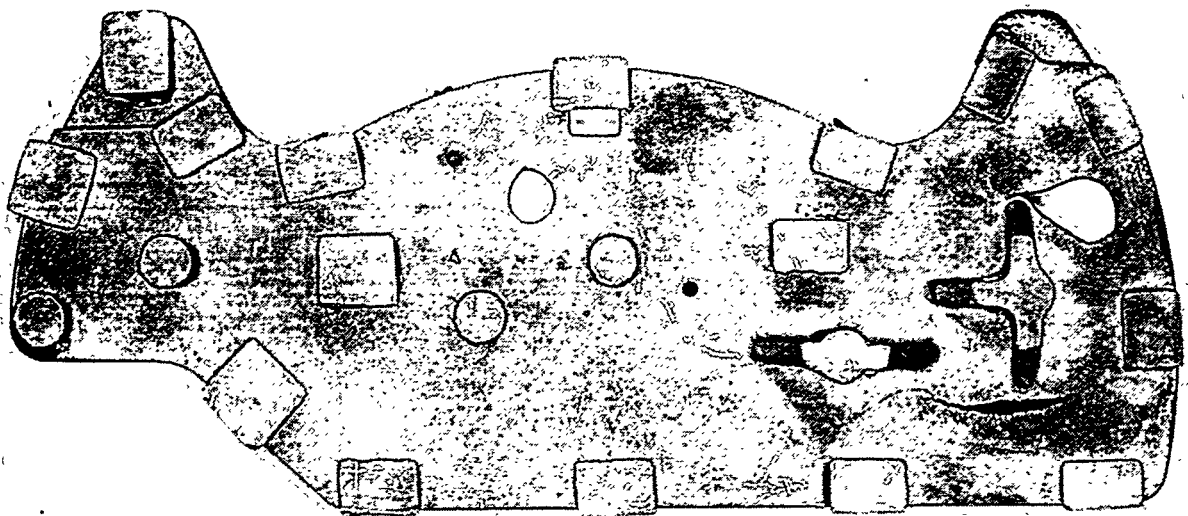


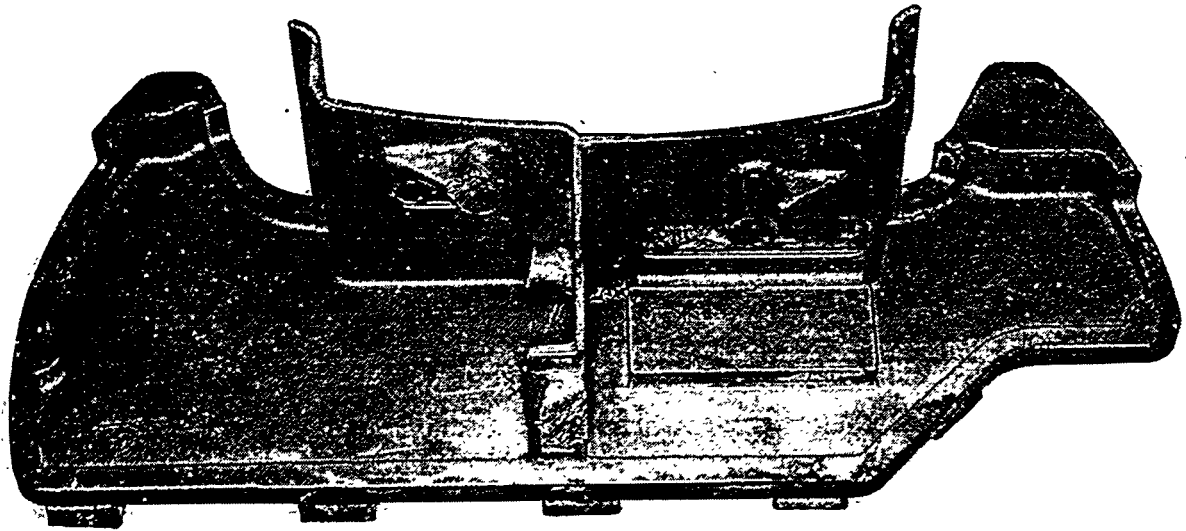
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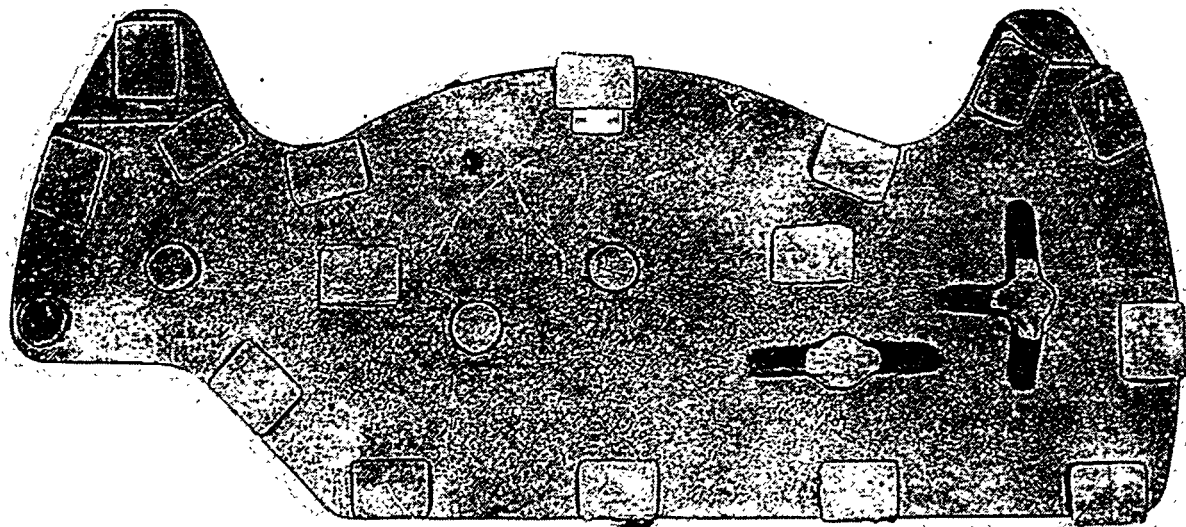


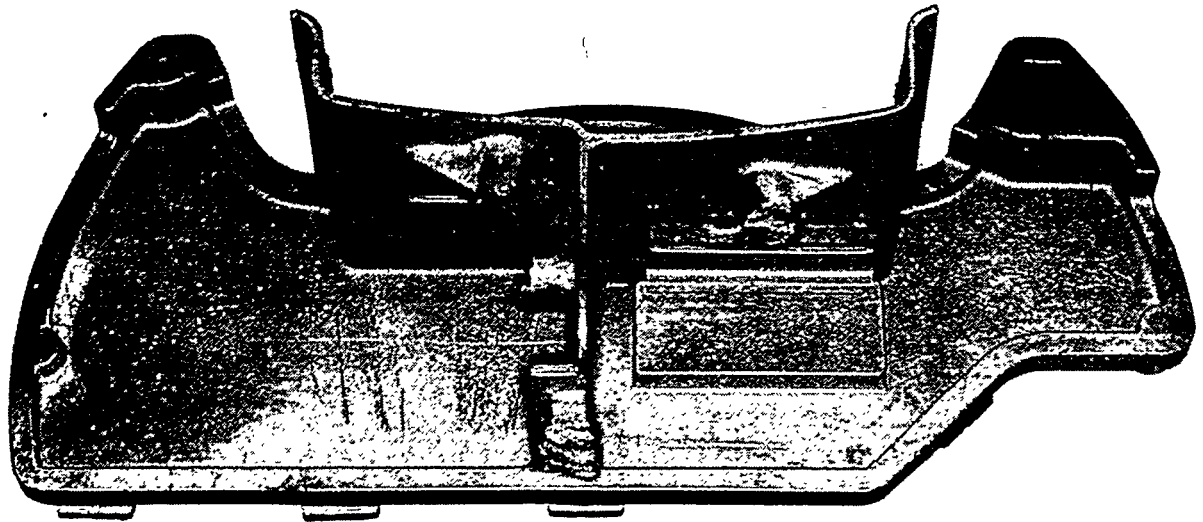
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S/N 35





S/N 36

