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Charles F. Draut and Don A. Homan

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A SEMI-AUTOMATED X-RAY GAUGING PROCESS CONTROL SYSTEM

C. F. Draut and D. A. Homan

Monsanto Research Corporation
Mound Laboratory
Miamisburg, Ohio

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D. A. Homan

ABSTRACT

An x-ray gauging method was developed and a production gauging system was subsequently fabricated to control the quality of precision manufactured components. The gauging system measures via x-ray absorption the density of pressed finely divided solids held in a dissimilar container. The two dissimilar materials condition necessitated a "two scan" technique: first, the x-ray attenuation (absorption) of the empty container prior to loading and then, the attenuation of the loaded container are measured; that is, four variables. The system provided greatly improved product control via timely data feedback and increased product quality assurance via 100% inspection of product. In addition, it reduced labor costs, product cost, and possibilities for human errors.

HISTORICAL BACKGROUND

Several years ago, an Atomic Energy Commission Weapons Design Agency requested that Mound Laboratory generate a conceptual design for an automatic, adaptive controlled system for explosive component manufacturing.

Automated powder feeding, weighing, pressing, and gauging for detonator production offer advantages in addition to increased efficiency. With shrinking tolerances and the philosophy of absolute tolerancing, instrumentation is currently being taxed to the state of the art in several areas. Figure 1 shows a proposed system that would combine the control of an automatic powder feeder, a balance, noncontact and x-ray gauges, and a servo-controlled hydraulic press. The flexibility of the system should permit the optimization of component assembly by dimension, density, or any other process variable. High-level programming languages permit programming by engineering personnel and adaptability to changing processing parameters and product design. Several weapons programs and anticipated high-volume product quantities did not materialize, so the design agency requested that Mound stop development on the total system. The agency requested, however, that each subsystem be individually developed keeping an overall systems approach in mind.

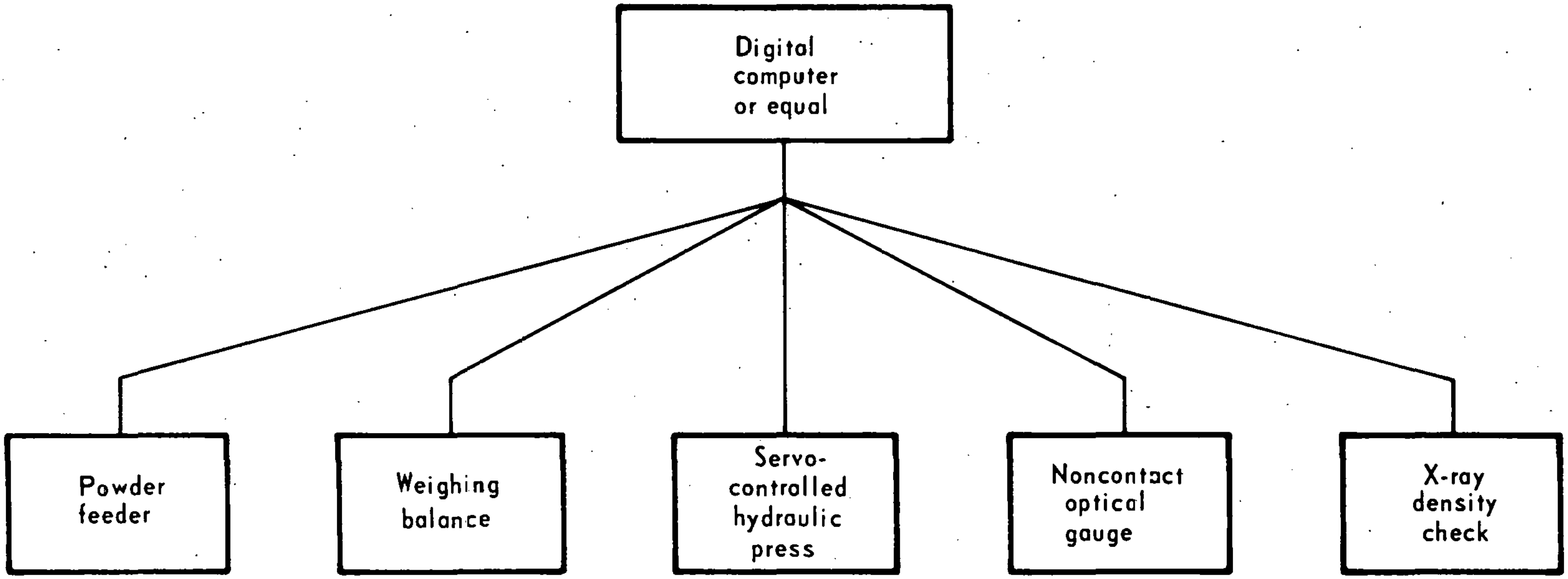


FIGURE 1 Computer controlled processing can increase the accuracy of the final product by selective assembly and feed forward control where subsequent process control set points are determined by the gauge result of a previous production step.

INTRODUCTION

With the requirement for a production-oriented, nondestructive method for 100% gauging of pressed-material components to ascertain density, an x-ray gauging system was developed. Previous methods for the control and measurement of the density of pressed-material components relied on careful control of weight and dimensional parameters, complemented by a statistical sampling of the components to calculate the material density. This procedure was functional but was time-consuming and limited because only a small portion (4%) of the total product was sampled. However, 100% nondestructive determination of density could achieve several advantages: better product control through timely feedback on the density of each component; inspection of 100% of the components to eliminate all rejects which might exist; and quick and relatively inexpensive quality control.

Several nondestructive testing methods were considered for density determination, but an x-ray gauging method was chosen because of the availability of a commercial x-ray system which utilizes a unique pulse-generating electronic circuit that produces short burst of x-ray energy less than 1% of the time, and thus keeps the emitted radiation at a low value for utmost operator safety.

A production gauging system was fabricated which used a commercially available Sheffield Measuray, Model 40PT, noncontact x-ray gauge. (1) The system included a semiautomated material handling subsystem to transport and position the components to be gauged concentric with the collimated incident radiation. A computerized automatic data acquisition and documentation subsystem was developed to collect and store the attenuation data of the two scans (empty container and loaded container) and to compute and print out the final density values. The system is shown in Figure 2.

X-RAY GAUGING

The principle behind x-ray gauging is the differential absorption of x-rays due to density and thickness variations of samples placed between the source of x-rays and the detector (pickup cell) according to the formula (2)

$$I = I_o e^{-\mu\rho t} \qquad (1)$$

where

I = Intensity of transmitted radiation,
I_o = Intensity of incident radiation,
μ = Mass absorption coefficient of the sample,
ρ = Physical density of the sample, and
t = Thickness of the sample.

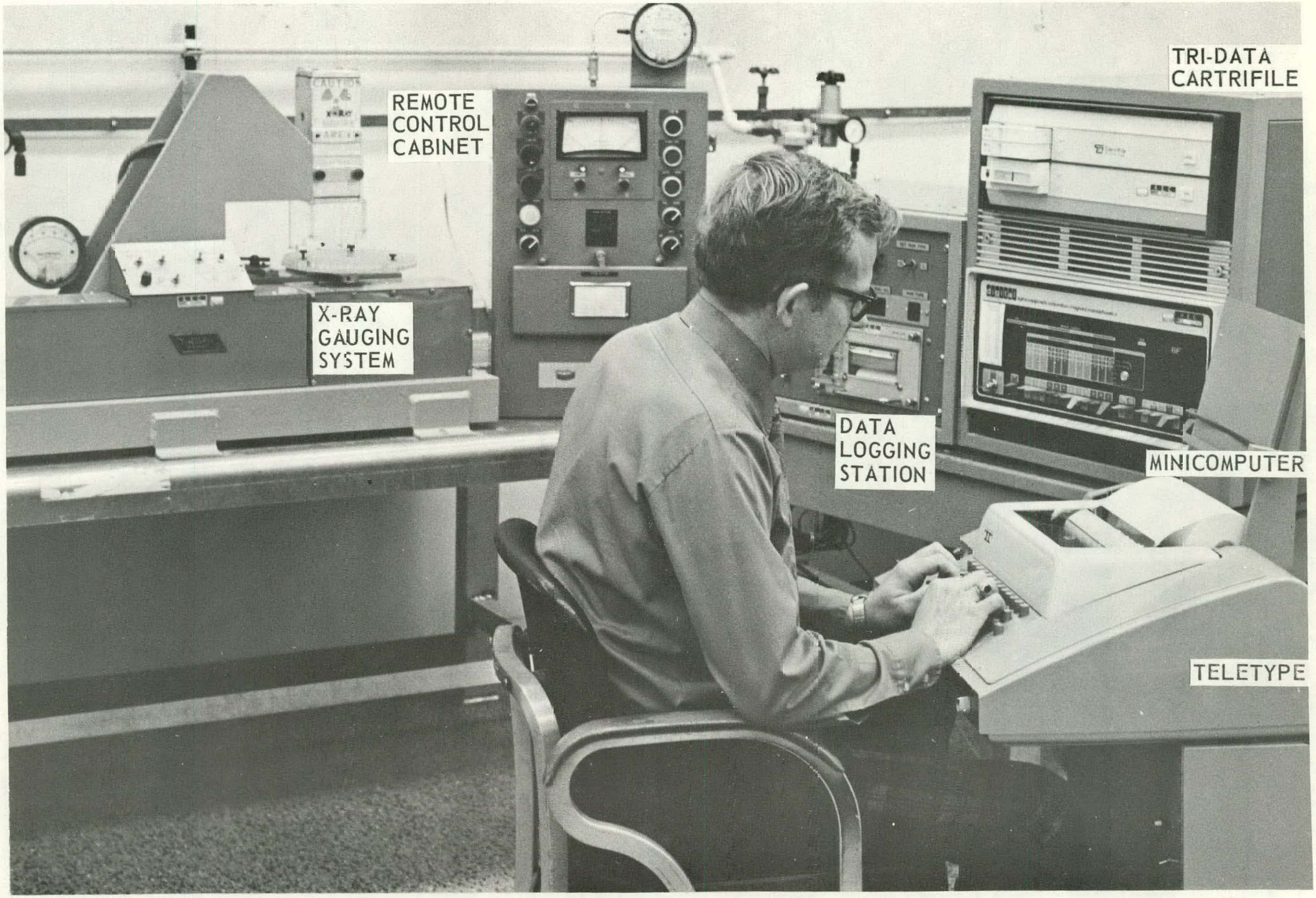


Figure 2 - A semiautomated x-ray gauging system was equipped with computerized data acquisition and documentation to speed density calculations and to eliminate recording error.

As a sample (component) is passed between the source and the detector, the energy directed at the detector is attenuated. Minute changes in attentuation are measurable, and thus very slight changes in density and/or thickness can be detected. To use the system for measurement, however, either the thickness or the density must be constant. If the thickness of the material is uniform, recorded changes are changes in density. If uniform density can be assumed, the system serves equally well as a thickness gauge. This inherent characteristic of the system, of being unable to distinguish between changes in density and thickness, is the origin of the term "DXT" (Density Times Thickness). Readout on most commercial DXT gauging systems is in terms of some predetermined density or thickness and a plus-or-minus percentage deviation from nominal.

The basic components of the DXT gauging system are an x-ray source, an aperture plate to collimate the incident radiation, and a detector or pickup cell to monitor the remaining radiation signal (Figure 3). The analog meter readout scale was set up to indicate percent deviation with zero at center and +5% and -5% end points. The system can be calibrated, however, with end points up to ±10%.

As contrasted with the description previously cited of two variables (i.e. sample thickness and sample density), our problem was more complicated because the need was to measure the density of pressed finely divided solids encased in small aluminum containers and thus there became four variables to consider, namely:

1 Container material density - aluminum.
2 Container material thickness - aluminum.
3 Pressed material density.
4 Pressed material thickness.

Figure 4 is a drawing of a typical aluminum container, and Figure 5 illustrates the material pressed into the container.

The desired gauging method should consist of only a measurement of pressed material density with suitable means for eliminating the other three variables. The contribution of the aluminum container density was considered to be negligible within a given lot of aluminum since it would affect all results equally. Laboratory tests indicated that the variation in aluminum container thickness could not be neglected, and thus the system and process developed included two DXT scans, one scan of the empty container prior to loading and a second scan of the loaded container.

The x-ray thickness gauge used was also equipped with a subsystem by which the thickness of the pressed material could be measured by physical contact, and the x-ray gauge could be corrected by the variation indicated by the thickness measurement. Under this arrangement, the density readout of the x-ray gauge

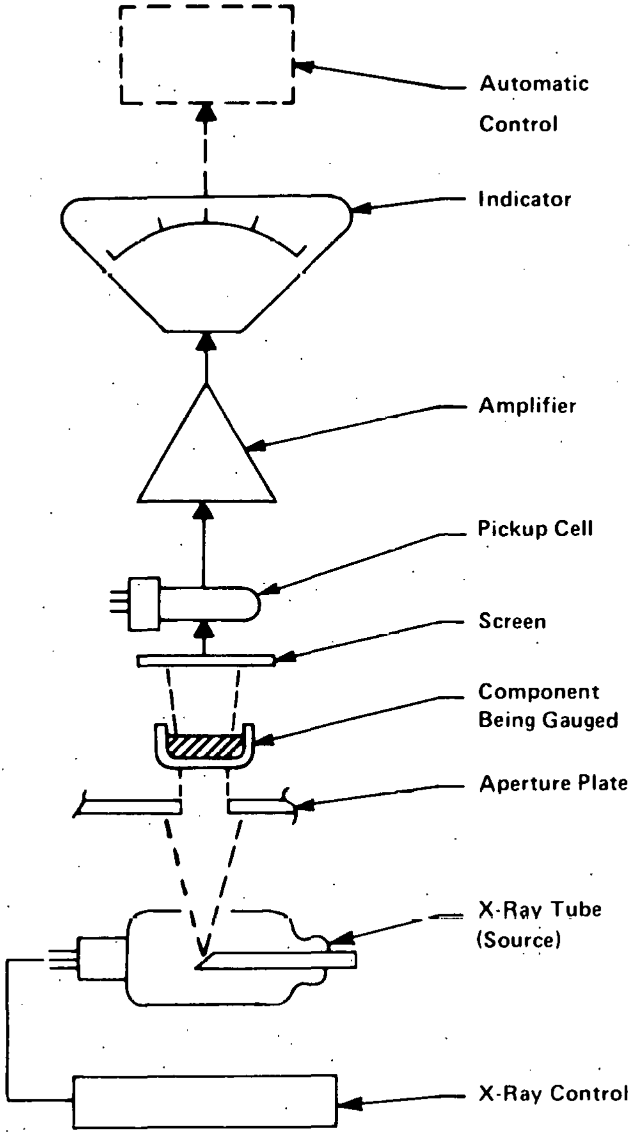


Figure 3 - The basic components of an x-ray gauging system.

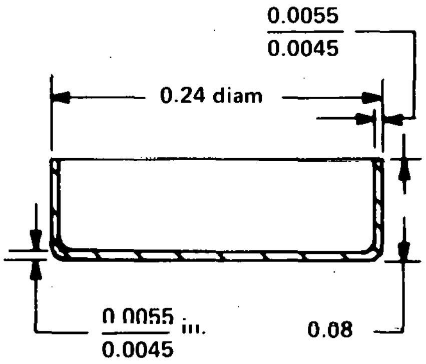


Figure 4 - The range of material thickness of the aluminum containers varied with x-ray attenuation.

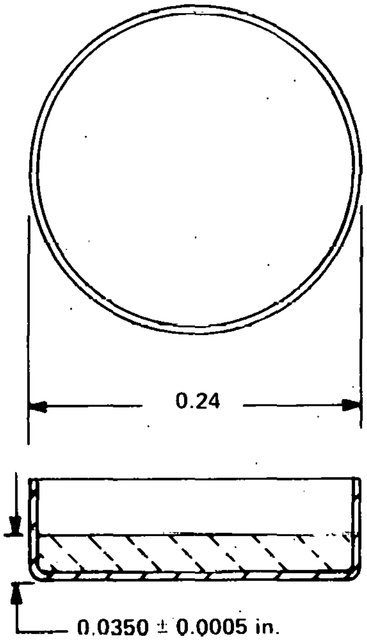


Figure 5 - The manufacturing process precisely controls the depth of the material pressed in a container.

is not greatly affected by thickness change in the pressed material. Laboratory test results, performed on normal process-controlled, precision-manufactured components, indicated that the range of the thickness change of the pressed material produced negligible influence on the density values. Thus, of the four variables originally stated, only two presented themselves as values to be determined, aluminum container thickness and pressed material density.

One can obtain a readout proportional to the density of the pressed material with samples of nominal pressed material density, samples of nominal aluminum thickness, and calibration for a percentage deviation in the pressed material density.

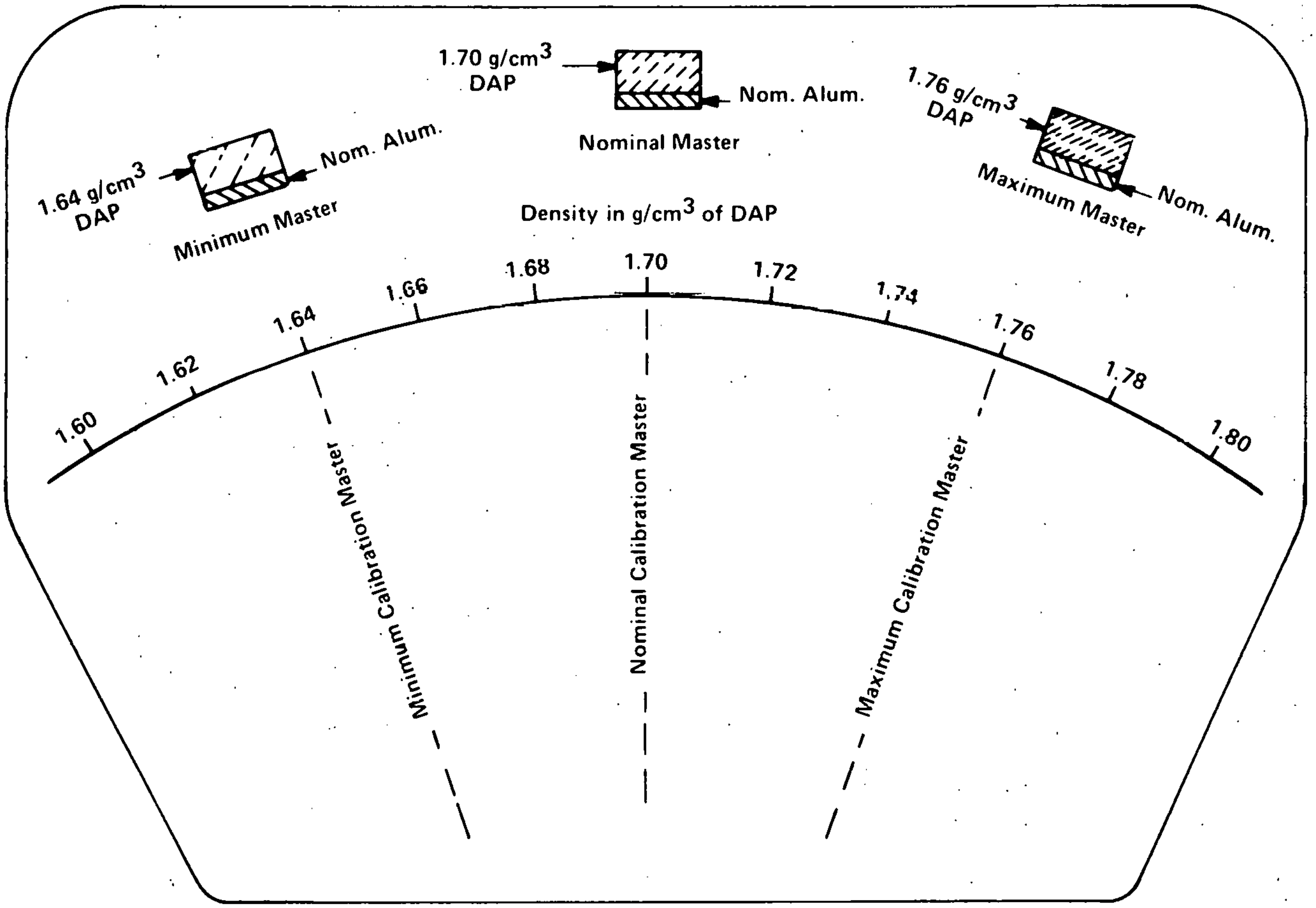
METHOD OF OPERATION

To explain the gauging method, we will use as an example the determination of the density of a pressed diallyl phthalate plastic (DAP) in analuminum container. We will assume the DAP density range of interest is 1.640 to 1.760 g/cm^3 with a nominal value of 1.700 g/cm^3, and the thickness of the aluminum container varies between 0.0055 and 0.0045 in.

These requirements are depicted in Figure 6 which shows the analog gauge meter calibrated directly in DAP density based on three known standards of the pressed DAP material resting on a nominal thickness aluminum container. The value of the nominal aluminum container used for each calibration setup is established by using a mean value of the coiled stock material from which a given batch of containers was fabricated. This selective means of determining the aluminum nominal thickness produces smaller corrections to be made on the results of the second scan of the loaded container. For the sake of clarity in the description of the procedure, we will assume the nominal thickness for this batch of aluminum containers to be 0.0049 in. With the scale thus calibrated, one can now implement the density inspection.

First, all of the empty containers are gauged on the DXT gauging system (first scan) with each container resting on a 1.700 g/cm^3 density DAP standard. An aperture plate with a 0.100 in. diameter opening was used to collimate the conical incident radiation.

The parts being gauged were rested as close to the aperture opening as possible. The indicated results will be displaced to the right or left of the center scale depending on whether the container is thicker or thinner, respectively, than the 0.0049 in. thick nominal aluminum sample. These results will be stored for later reference by the on-line-computer data-logging system.



Nominal Aluminum Thickness=0.0049 in.

Figure 6 - The analog meter scale is calibrated in terms of density (DAP).

The next step is to press the DAP into the empty containers. The loaded containers are then regauged on the DXT gauging system (second scan), but this time with the nominal 1.700 g/cm^3 density DAP standard removed. The values obtained for the loaded containers (second scan) must then be corrected by the amount their respective container deviated from the nominal condition in the first scan (empty container gauging). The density of the pressed DAP in each container is then determined. The density value obtained for the DAP pressed in the thin container must be increased by the same amount (density in g/cm^3) that the thin container was below the nominal condition. The value obtained for the DAP pressed in the thick container must be decreased by the same amount (density in g/cm^3) that the thick container was above the nominal condition.

EQUIPMENT

Material Handling Subsystem

A semiautomated material handling subsystem was designed and fabricated to transport and position the components to be gauged concentric with the collimated incident radiation. Once the operator installs a carrier filled with parts (unloaded aluminum cups or loaded components) on the spindle, he has only to activate the start button and the carrier is automatically indexed so that each position in the carrier is passed through the x-ray beam and counted. The dwell at each position is timed to allow the x-ray to stabilize and the system to record the attenuation value before indexing to the next position. After the contents of all the 50 positions are gauged, the indexing of the carrier is automatically stopped until the start cycle is reinitiated by pushing the start button. There is also a control that the operator can use to quickly index the carrier to a desired position, while eliminating the time required to stabilize the x-ray at all interim positions. This control keeps the indexing mechanisms in sequence and allows the operator to turn the x-ray on and complete the remainder of the cycle as initially programmed, having omitted examination of the undesired number of positions.

The system includes swivel plates that hold the thickness masters for system calibration and standardization of the mean value. The bottom plate contains one working master each for simulating the minimum, mean, and maximum finely divided solid loads (DAP in this situation); the top plate contains the working master simulating the aluminum cup thickness. By a simple rotation of the lower plate, pressed solid density masters can be placed in the x-ray beam with the cup master. Any of the necessary combinations of the working density masters can be obtained easily without manually placing the miniaturized parts in a nest in the path of the x-ray beam. For measuring the density of the actual loaded cups with this system, a clearance hole was provided in the lower swivel plate for the x-ray beam to pass through and gauge the loaded cup without interference. (Figure 7).

Control of the x-ray and thickness adjustments can be made from the remote control cabinet.

Data Acquisition and Documentation Subsystem

To simplify and to provide an accurate and impartial interpretation of the results, the polar chart recorder used on an earlier x-ray gauging system was replaced by a data logging station containing digital electronics. As development progressed, experiments were conducted using a Digital Equipment Corporation (DEC) PDP 8/S minicomputer to manipulate and structure the data. Finally, to obtain greater speed, the PDP 8/S was replaced by a DEC PDP 8/F minicomputer with 8K of core.

The analog signal from the x-ray detection circuitry is converted to a Binary Coded Decimal (BCD) digital signal and transmitted serially to the computer where the data are massaged, stored, and printed. A Newport Model 2100-3 milliammeter is used as the analog-to-digital converter and a Sagetec model 1600 Data Link transmits the data.

A Tri-Data CartriFile, model 4196, with four tape cartridges is used to store the operating programs as well as Pass 1 data for each parts carrier tested. Two operating programs are used. One program is used to initialize the CartriFile tapes which will be used for data storage while the other program is used for the actual DXT parts testing. A flow diagram is shown in Figure 8.

Since the teletype, model ASR33, is used for input and output, much time is saved by storing the operating programs on CartriFile tape.

Focal is used as the programming language. This language was most familiar to the authors and core was not a limiting factor. Machine language could have been used for the programs if core space had been at a premium.

DXT Software

The computer not only accepts and reports data but, through its software, corrects the data as well. During setup and prior to gauging each carrier, nominal, maximum, and minimum density masters are x-rayed and the results are stored by the computer. The maximum and minimum density master values are used to compute a K factor to correct for the operator's misadjustment of the THICK and THIN limits where

$$K = \frac{0.12 \text{ g/cm}^3}{(\text{max} - \text{min})}$$

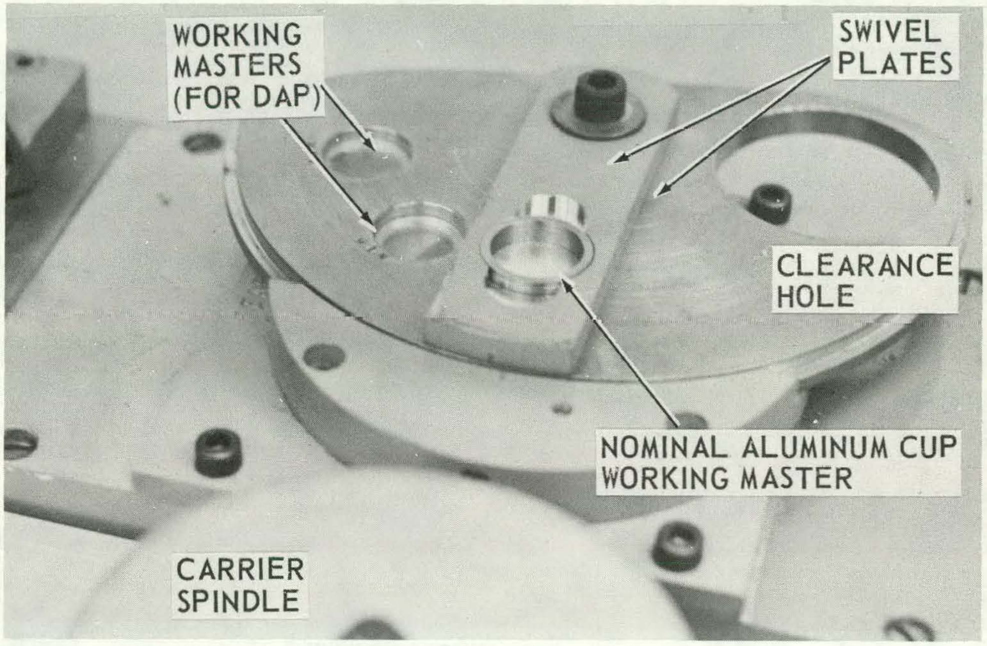


Figure 7 - Swivel plates containing the working masters hastened system calibration and standardization.

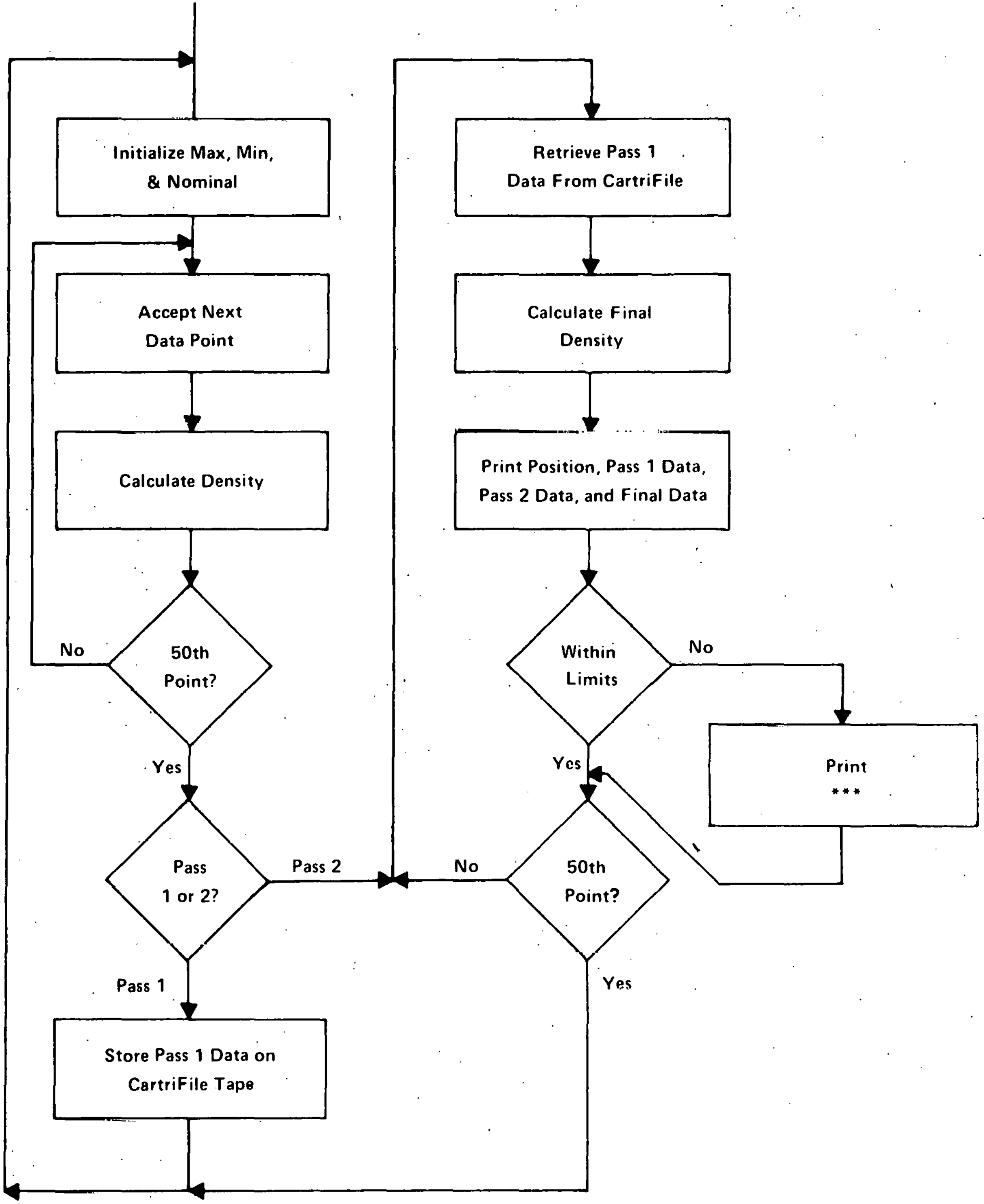


Figure 8 - The DXT operational program controls the system and documents the results without operator interaction.

During the first pass (unloaded cup) only the nominal density working master is used since the aluminum master is replaced by the cup being gauged. As each cup is x-rayed during the test, the raw data transmitted to the computer is converted to density units and corrected by the K factor so that

$$D_R = D_V K + 1.70 \qquad (2)$$

where 1.70 is the nominal density and D_V is the cup variation from nominal. The resultant density (D_R) is then printed by the teletype along with pass number, carrier number, and carrier position. After the fiftieth part has been gauged, Pass 1 data are printed as a record and for operator observation. The data are stored on the CartriFile tape for later use when these same cups are again gauged after being loaded with pressed solids.

Pass 2 gauging is done similarly to Pass 1 except no masters are used during the gauging. At the completion of Pass 2, Pass 1 data are recalled from the CartriFile tape and the final density is calculated for each cup by

$$\text{Density of pressed solids} = D_2 + (1.70^* \text{ g/cm}^3 - D_1) \qquad (3)$$

where D_1 equals the empty container measured value in g/cm^3 during Pass 1, D_2 equals the loaded container measured value in g/cm^3 during Pass 2, and *1.70 g/cm^3 represents an example of a nominal density of a given density range.

Final density values are printed on the teletype; those that are out of limits are followed by *** for identification.

SUMMARY

A nondestructive x-ray gauging system was fabricated for production use to control the quality of precision components. The semiautomated system with computerized data acquisition and documentation measures, calculates, and documents the density of 100% of the components which consist of finely divided solids pressed into dissimilar containers.

The system reduced the gauging and density calculation labor costs approximately 65% over a previous manually operated system, and it is not as highly dependent on the judgement and skills of the operator as was the manual system.

The automated documentation system reduced the opportunities for human error in density calculations and data recording, and greatly improved product control because of faster data feedback to control the line manufacturing operations. In addition, product quality assurance was increased because of the 100% inspection of the products with the secondary benefit of reduced product cost attributed to destructive examination of 4% of the product.

Logical extension of this technique should permit measurement of liquids, solids, or particulate matter which are contained in relatively less dense materials. Alternately, the density of materials in handling or shipping containers could be checked for density or scanned for density gradients.

ACKNOWLEDGEMENTS

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