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CONTINUED INVESTIGATION OF SOLID PROPULSION ECONOMICS

Task 1B
Large Solid Rocket Motor Case Fabrication Methods - Supplement Process Complexity Factor Cost Technique

DRA

Prepared for:

NATIONAL AERONAUTICS AND
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Large Solid Rocket Motor Case Fabrication Methods- Supplement Process Complexity Factor Cost Technique

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Principal Investigator: John Baird

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ABSTRACT

This supplement to Task 1B--Large Solid Rocket Motor Case Fabrication Methods--supplies additional supporting cost data and discusses in detail the methodology that was applied to the Task.

For the case elements studied, the cost was found to be directly proportional to the Process Complexity Factor (PCF). The PCF was obtained for each element by identifying unit processes that are common to the elements and their alternative manufacturing routes, by assigning a weight to each unit process, and by summing the weighted counts.

In three instances of actual manufacture, the actual cost per pound equaled the cost estimate based on PCF per pound, but this supplement recognizes that the methodology is of limited, rather than general, application.

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INTRODUCTION AND SUMMARY

This report describes a new approach to cost projection and is a supplement to a previously reported study, Continued Investigation of Solid Propulsion Economics, Task 1B: Large Solid Rocket Motor Case Fabrication Methods. It discusses the trade-offs entailed in 10 alternative methods of fabricating large rocket motor steel cases. The accompanying cost projections were based on available data or extrapolations of known costs. The technique used in this supplementary report is based on the relative complexity of each fabrication method with respect to a common standard. Since each fabrication method is evaluated in terms of relative complexity to the standard, the method has been termed process complexity factor (PCF).

Every operation in the fabrication of a steel rocket chamber requires a set-up, which means preparing the steel case material for the next operation and providing the necessary holding fixtures and machine tools. Consideration is given to the weight of the part before and after the operation. Because the set-up operation is common to all methods of fabrication, it has been given a factor of one. Operations considered to be twice the complexity are given a factor of two. This supplement describes in detail the PCFs assigned for each operation of the 10 process methods, which are described and illustrated as Figures 1 through 10 in the original report.*

In three instances, it was possible to compare projected with actual costs. Good agreement was obtained as shown in Table 2. No actual cost data exist for the other seven candidate fabrication methods, but to the extent that it has been demonstrated, the PCF technique appears to be valid and tends to substantiate the factors assigned to the other seven methods studied.

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* For ease of reading, the figures from the original report are reproduced in the appendix.

PROCESS COMPLEXITY FACTORS FOR PROCESS AND SHIPPING OPERATIONS

Process Operations

Set-up operations in the manufacture of very large components are costly in terms of labor hours and are common to practically every process operation. For example, the set-up operation associated with machining a motor case component of 260" diameter requires movement of the part to the location of the machining equipment, transferring the part to the table of the machine, locating it to find a best center if the operation is of a clean-up nature, or locating the center to close tolerances if the operation is a finish machining operation. The set-up operation in preparation for a longitudinal weld in parts at or near the motor case diameter requires moving the detail parts to the location of the welding fixtures, positioning the details in the fixtures, making adjustments to minimize weld gap, installing applied tooling, and positioning the details in the fixture in suitable relation to the welding equipment for completing the weld. For large parts, the set-up operation includes a rigging crew and plant equipment, such as overhead cranes, fork lifts, boom crane, flat bed trucks, and tractors. An average set-up operation requires a crew and equipment for an 8 hour shift. An average rigging crew is five persons. In addition to the cost of the crew, there is an associated expenditure for standby and supervision. A PCF of 1 is applied whenever a set-up operation or its equivalent occurs.

Where significant operations are required in addition to set-up, and these require a work force larger than a machinist and a helper, or welder and helper, a factor of 1 is added. The PCF in that case is then 2.

To account for the cost of material lost in a processing operation, a PCF is applied that represents the fraction of material lost. For example, cutting the flat patterns of details from sheet material requires a set-up operation to locate the sheet for layout and make the required cuts. In the cutting, 15 percent of the plate surface area may be removed and become scrap. The PCF for the set-up operation is 1; 0.15 is added to account for the material lost. The factor for the operation is 1.15. This method of assigning an economic penalty to losses incurred in machining and trimming material is not based on a direct accountability in dollars for the material lost and its scrap value. Accounting for material loss on a direct dollar basis would require a different material loss factor for each alloy selected to relate it to the cost for the typical set-up operation. The material loss factor is intended to credit the manufacturing process with higher material utilization.

Reduction-Forging

The reduction-forging operations identified as slab and plate are performed with equipment that is specifically and continuously set up to do those operations. The material is moved to the process locations by automatic handling equipment from a central control station, which is manned continuously. The factor for the slab and plate operations is 0.6.

Cutting-Machining

Each cutting-machining operation requires a set-up. These set-ups vary according to the nature of the operation. For example, using plasma arc cutting equipment for cutting flat patterns from plate requires labor for moving the part to a lathe and locating it for precision machining operations. The total cost of the two types of set-up operations is similar. All cutting-machining operations are assigned a factor of 1, plus a contribution that depends on the percentage of material trimmed or machined away. This factor takes into account the machining hours as well as the cost of material that is recovered only as scrap.

Forming

All forming operations require the equivalent of a set-up operation. The simpler forming operations, such as rolling a sheet to a cylindrical contour or rounding a cylindrical weldment after welding, are assigned a factor of 1, since the forming operation itself is performed as part of the set-up. The roll extension operation includes a set-up, plus significant operations after set-up. The roll extend and roll extend final operations are assigned a factor of 2; 1 for the set-up and 1 for the forming operation.

Welding

Welding operations require a set-up and significant operations after the set-up to make the weld joint and qualify it, using specified non-destructive test methods. A factor of 1 is applied for the set-up and 1 for the operations, or a total factor of 2. In the weld operation, which is considered the normal case for this evaluation, two longitudinal weld seams are made in a cylindrical section 8 feet long. If more than two seams are required in the equivalent cross section, the assigned factor is increased proportionately.

Heat Processing

The heat processing steps* are performed in furnaces of the car bottom type without applied tooling. The incremental labor for these steps is considered to be negligible and a weighting factor of 0 is applied. The hardening heat treatment process identified by H.T., when it is performed on 260" diameter parts at near final thickness and where part length exceeds 24", is considered the equivalent of a set-up since it entails significant assembly of the part with tooling. Labor requirements during the furnace time are considered to be negligible, and a factor of 1 is assigned for the H.T. operation. Hardening heat treatments performed on plate or other semifinished forms that do not require tooling are assigned a factor of 0.

The heat processing steps are identified primarily to display process complexity and the potential of diminished structural properties.

Assembly

The assembly of case structural elements with mechanical joints that are proof tested separately with tooling is considered to be the equivalent of a set-up operation and is assigned a factor of 1.

Proof Test

The proof testing operation is considered to be the equivalent of a set-up operation and is assigned a factor of 1.

Shipping Operations

The factors that could be assigned to shipping operations vary widely depending upon the relative locations of the operations and the form in which the material is shipped. Normal routes are selected, and the factor

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* Identified by Roman numerals in Figures 1-10.

is based on estimated equivalent operations. The loading and off-loading of raw and flat material, such as ingots, slabs, and plate, on readily available flatcars is considered to be the equivalent of one-half of a set-up operation.

The shipment of parts for the 260" diameter motor is considered to represent the equivalent of two set-ups, one for loading and one for off-loading, and significant operations in transit; a factor of 5 is assigned. It is difficult to justify this factor rigorously on the basis of actual experience, since the total cost for the movement of the large parts accomplished to date is not charged to the move in a rigorous fashion. The charges for loading and off-loading are not easily identifiable in the carrier's and manufacturer's accounting. In-transit manpower for the one-time moves was supplied in part by the highway divisions of the states in which the moves were accomplished. The factor assignment is considered to be reasonable, since each mode in the shipment of a large part will require a certain number of calendar days, no less than five persons and leased equipment costing more than $1,000 a day.

Table 1 shows the PCF's of each of the process methods studied, with and without shipping costs. In general, the ranking of fabrication methods is the same for the simple count and the weighted count. The weighted count, however, represents more closely the relative cost for the several methods studied. In the discussion which follows, a portion of the content of the report is repeated for convenience and to highlight the conclusions indicated by the PCF method.

Table 1

260" CASE ELEMENT MANUFACTURING METHODS - WEIGHTED COUNT SUMMARY

Method	Number of Operations	PCF	\$/lb Incl. Shipping	PCF Less Shipping	\$/lb Mfg. Costs Only
Cylindrical section with weld joints (13,200 lbs)					
Form and weld	12	8.9	6.7	8.4	6.4
Forge and machine-roll extend	16	21.8	16.6	16.3	12.4
Form and weld-roll extend	17	25.0	19.0	14.5	11.0
Cylindrical section w/mechanical joints (15,800 lbs)					
Forge and machine	15	14.0	8.9	8.5	5.4
Forge and machine-roll extend	19	28.9	17.7	18.4	29.0
Form and weld-roll extend	20	32.0	20.0	16.5	26.0
Y joint ring (5,500 lbs)					
Form and weld	12	9.3	16.9	8.8	16.0
Forge and machine	13	16.1	29.0	10.6	19.4
Spherical surface (910 lbs)					
Press-spin and machine	8	6.1	67.0	5.6	62.0
Spherical surface-gore					
Complete shell (15,800 lbs)	8	22.9	14.5	22.4	14.2
Form-gore only (1,580 lbs)		2.04	12.9	1.54	9.7

EVALUATION OF FABRICATION METHODS

Fabrication of Cylindrical Section with Weld Joints

Table 1 summarizes the PCFs in each of the process categories identified. The summary is presented in this form so that it is possible to identify the process elements that contribute to the total factor for each method evaluated. The table also identifies the method and the element and gives the total count and the total count less the contribution for shipping operations. The entries for Figures 1, 6, and 8 apply to three different fabrication methods that produce a cylindrical section with welded joints. The form and weld method is seen to have the least total count, or 8.9. The forge and machine preform, roll extended, has a total count of 21.8; and the form and weld-roll extend has a total count of 25. The form and weld method is seen to be the least complex and potentially least costly of the three methods evaluated.

From Table 1 it can be seen that the operations contributing to the high relative counts of the roll extended processes are the forming operations and the shipping operations. It should be noted that for Figure 8 the roll extension process does not reduce the expense or eliminate welding as a factor influencing cost. The roll extension process requires moving a full diameter part significant distances; the shipping step could not be eliminated without relocating or constructing new facilities to allow this process to be accomplished at a motor case fabricator's plant. The forming operation is another major contributor to the high factors of the roll extension process, because it takes two steps to complete an operation that can be completed with greater efficiency in one step by another method. For the form and weld process, the material is reduced to final thickness at the mill. For the processes shown in Figures 6 and 8, thickness is partially reduced either at the mill to produce slab or by the forger to provide a forged ring preform. The final step in reduction of thickness is performed in a separate step using special equipment that is suitable for that operation only. Since this situation exists, there cannot be economic justification for use of the more complex route unless other technical advantages are seen to exist. Technical advantages for the roll extension processes are not apparent, since the hardening effects of cold working during the roll extension process would have to be removed by heat treatment to achieve the highest possible toughness.

The evaluation assumes that the processes and required tooling are developed and that the process is successful. No attempt is made to apply factors that represent in-process loss, process repeats, or repair. It is expected that the degree of nonsuccess with the several fabrication methods will be similar. For example, the process shown in Figure 8--the form and weld preform, roll extended--will require welds in thick plate that will have to be repaired with a frequency similar to that for the form and weld process, which does not require roll extension. It is expected that faults in parent plate or forgings will be discovered during the roll extension process, which will require at least grinding and perhaps a weld repair. Where process or material improvements are achieved, they will apply equally to all three methods. The development of alloys with increased process tolerance or tolerance to flaws will improve the process and the final reliability of part equally for the three methods evaluated. If, for example, weld processes are developed and characterized to the extent that nondestructive testing can be reduced or eliminated--with the exception of any special requirements on welds necessitated by the cold reduction process--the advantage would apply equally to the form and weld method and the form and weld preform roll extended method of producing a cylindrical section.

When the three manufacturing methods are studied and the operations and their sequence are understood, the relative total counts for the processes appear to reflect the complexity and potential cost. Comparison of the process shown in Figure 1 with that in Figure 8 shows that the latter has about twice the total count when the influence of shipping on the count is removed. This result appears to be consistent, considering that the roll extension process is initiated after a sequence of operations that would have produced a cylindrical section ready for weld assembly to the motor case.

Fabrication of Cylindrical Section with Mechanical Joints

Fabrication methods using mechanical joints are included in the consideration primarily as an alternative to motor case assembly methods. In general, the discussion above for cylindrical sections with weld joints applies in comparing the three methods for fabricating these sections with mechanical joints. Table 1 indicates that forge and machine methods will produce a cylinder 40" long. However, current capability may be limited by existing forging equipment, ingot size, or both. In evaluating the methods in a consistent manner, it must be presumed that the equipment, ingot size, and techniques exist to produce cylinders of a normal length of 90" by all methods. The 90" length is established as a basis for comparison and is based on plate rolling width normal maximum. The advantage in processing cylindrical elements with 260" diameters and lengths in excess of 90" will probably be offset by costs incurred in supplying the additional tooling to manipulate large pieces. This cost would be in addition to the costs of tooling for the other operations associated with manufacture of very long cylindrical sections. The forge and machine method of producing case cylindrical sections with mechanical joints appears to be most advantageous. The basic reason is that the forging process, which is capable of producing all required thickness reduction to the finish machine step, is used for that purpose. In the processes shown in Figures 5 and 7, forged and formed and welded preforms are used at only part of their capability; other processing methods and steps are used to complete thickness reduction with added complexity and cost.

The cylindrical sections with mechanical joints are shown to be proof tested as segments. In an actual production effort, this route may not be elected. The segment proof test is used in this analysis since it is consistent for all methods, the next step being assembly to the motor case. While the total count can be made to vary by specifying that assembly and test be accomplished at the motor loading location, the rank of these methods relative to the form and weld method will not change. A variation in motor case design that would permit segmented propellant loading is not considered.

Fabrication Methods for Y Joint Ring

Table 1 indicates an advantage for the form and weld method of manufacture for Y joint rings. Examination of Table 1 indicates that forging operations and shipping are the significant factors favoring the form and weld method. For process considerations alone, the differences seem to be less significant. When the most probable sequence of operations is used in the form and weld method, the processing advantage for the method is lost. The advantage that remains then for the form and weld method results only from the shipping operation. If the most advantageous processes are to be selected, other factors must be reviewed as follows:

- The form and weld method of fabricating Y rings will not require new tooling. The development and characterization of the weld process for the thick section will be required and will always represent a problem that is separate and different from weld process development for other joints in a motor case. In addition to the increased thickness, the hardenability of the weld deposit in thick sections will have to equal that for the plate. The welded preform will be heat treated when it has a thickness that is at the limit of hardenability for applicable alloys. The scope of the weld process development and characterization for the thick section will be as extensive as is required to demonstrate uniform high toughness and freedom from fault occurrence, including consideration of loss in effectiveness of NDT methods resulting from thickness.

- The forging process has been reduced to practice; improvements to that practice can be achieved reliably with relatively small expenditure for tools.

The selection of a method must be based on a detailed evaluation of the thick section weld development process and its cost compared with the shipping cost for the forgings, and conclusions that are drawn must be based on the number of units to be produced.

Case Fabrication Methods for Spherical Surfaces

The pressing or spinning of relatively thick-walled, double-curved surfaces is compared with the process of cold pressing spherically contoured gores from plate. Table 1 indicates that the advantage of the cold pressing approach results largely from the poor material utilization in the press or spinning approach. Completing a weld assembly of spherically contoured parts prepared by other than cold pressing methods appears to be impractical.

Weighting Factors and Relative Costs

The ranking of the several fabrication methods in terms of their PCFs would be more rigorous if they could be related in some fashion to dollars. In the fabrication process methods studied, this relation could only be determined for those instances where actual costs had been developed for a specific fabrication method. The methods are the process of form and weld fabrication of a cylindrical section with weld joints and the forge and machine manufacture of a Y joint ring. The cylindrical section has a total of 8.4 without shipping. The forge and machine manufacture of a Y joint ring has a total of 10.6 without shipping. The approximate cost for heavily machined Y joint forgings, which weighed 5,500 pounds, procured in the Aerojet 260" motor program was $20 per pound. The average cost for the motor case was $10 per pound; the heads cost $16 per pound; and the cylindrical section costs $6 per pound. A 90" long cylindrical section weighs about 13,200 pounds. The PCF per pound for the Y ring is 19.4×10^{-4} and 6.40×10^{-4} for the cylinder. The actual cost to manufacture Y rings and cylindrical sections is $20 and $6, respectively, which are in good agreement, as shown in Table 2.

To project the cost of manufacturing a head consisting of a complete shell fabricated of formed gores and a Y ring, the PCFs for the complete shell and Y ring were added and the sum was divided by the combined weight of the shell and Y ring. The cost per pound estimated using this method is $15.70; which agrees with the actual cost for manufacturing the head of approximately $16 per pound (see Table 2).

The correlation of projected and actual costs for three methods of case fabrication tend to substantiate the PCF technique and provide confidence in the economic evaluation of the other seven fabrication methods. For the operations involved, it is reasonable to estimate that fabrication of cylindrical sections with weld joints using the roll extend process will cost approximately twice as much as manufacture of cylindrical sections using the form and weld process. For fabricating spherical surface elements, the press-spin and machine method will cost approximately six times as much as the cold pressing method of forming gores.

The multiplier of 10,000 was evolved during this study as a factor relating actual cost per pound with the PCF. For the material used in the 260" motor case, a correlation has been demonstrated. However, the same multiplier may not extend to other size motors or case materials. Further study is required to prove that the PCF technique is a rigorous method of cost projection and that the 10,000 multiplier has universal application.

Table 2

260" CASE ELEMENT MANUFACTURING METHODS WEIGHTING FACTOR AND ACTUAL COST CORRELATIONS

Case Element/Method	Approximate Weight (lbs)	Estimated Cost* ($/lb)	Actual Cost ($/lb)
Cylindrical section form and weld	13,200	6.4	$ 6.00
Y joint ring forge and machine	5,500	19.4	20.00
260" case head Y joint ring + complete shell	21,000	15.7	16.00

$$* \quad \text{Estimated cost (\$/lb)} = \frac{\text{PCF} \times 10^4}{\text{Weight}}$$

Appendix

PROCESS METHODS FOR FABRICATING
LARGE SOLID ROCKET MOTOR CASES

FORM AND WELD — CYLINDRICAL SECTION WITH WELD JOINTS

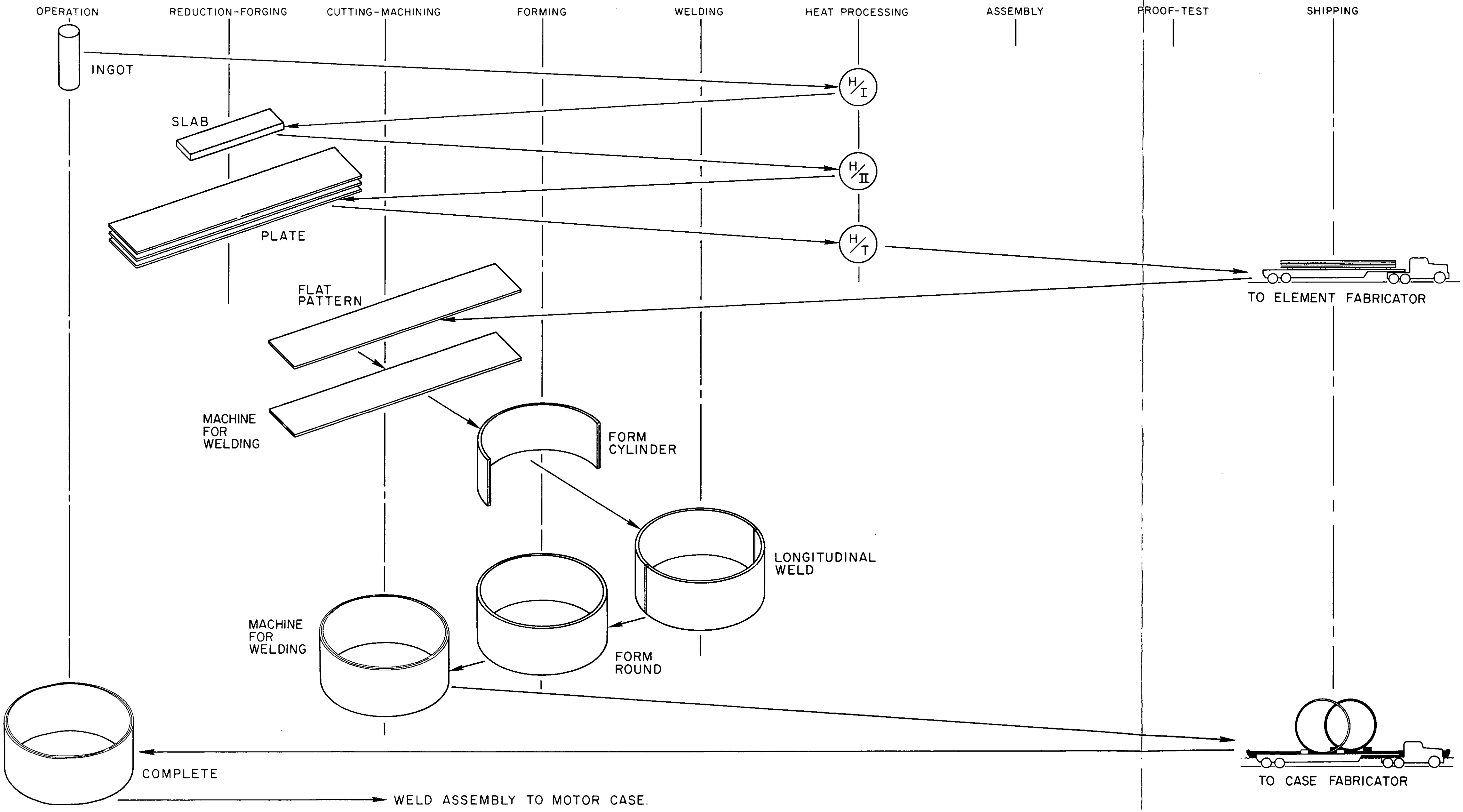

FIGURE I

FOLDOUT FRAME 1

FOLDOUT FRAME 2

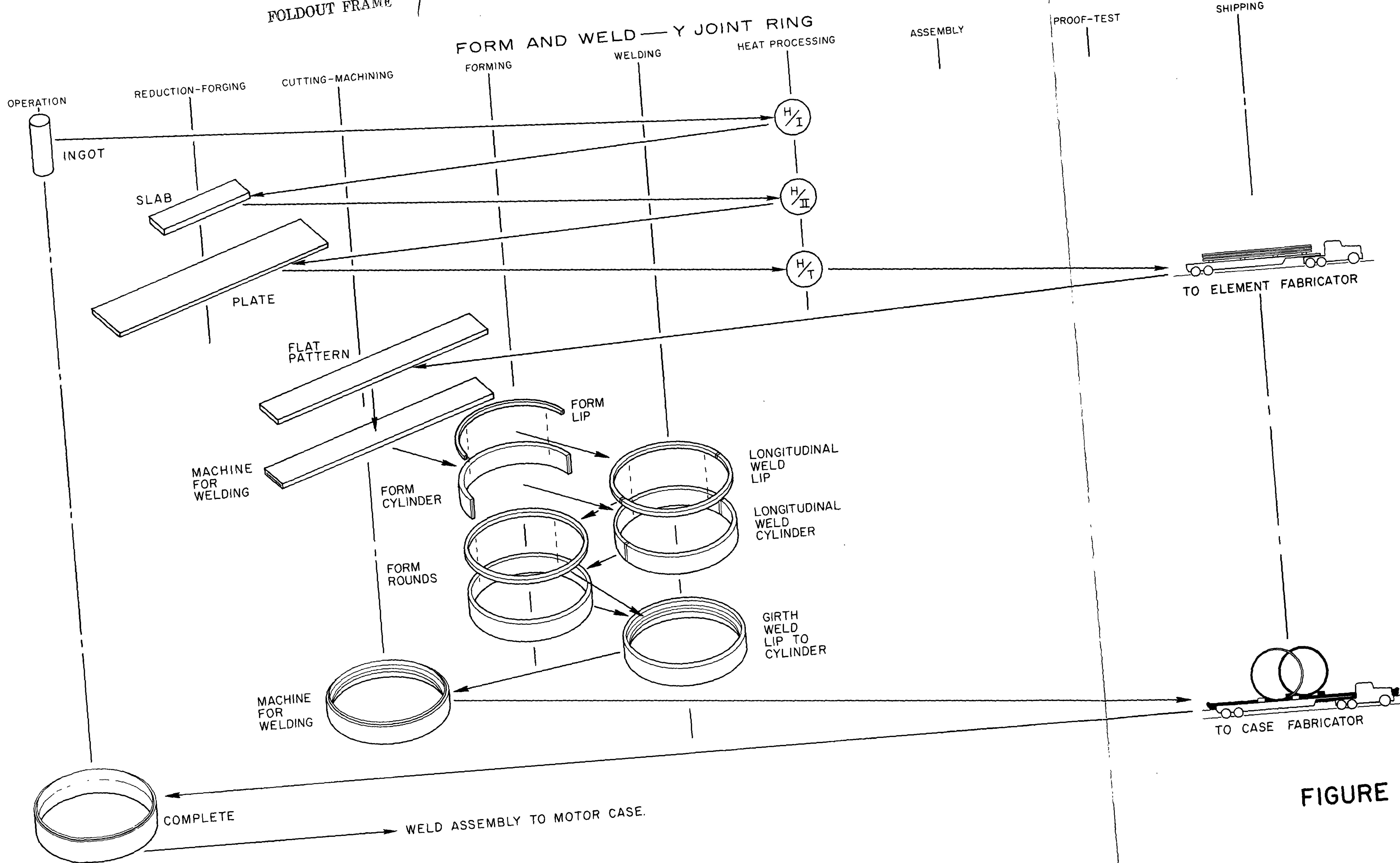

FIGURE 2

FOLDOUT FRAME 1

FO... ...AME 2

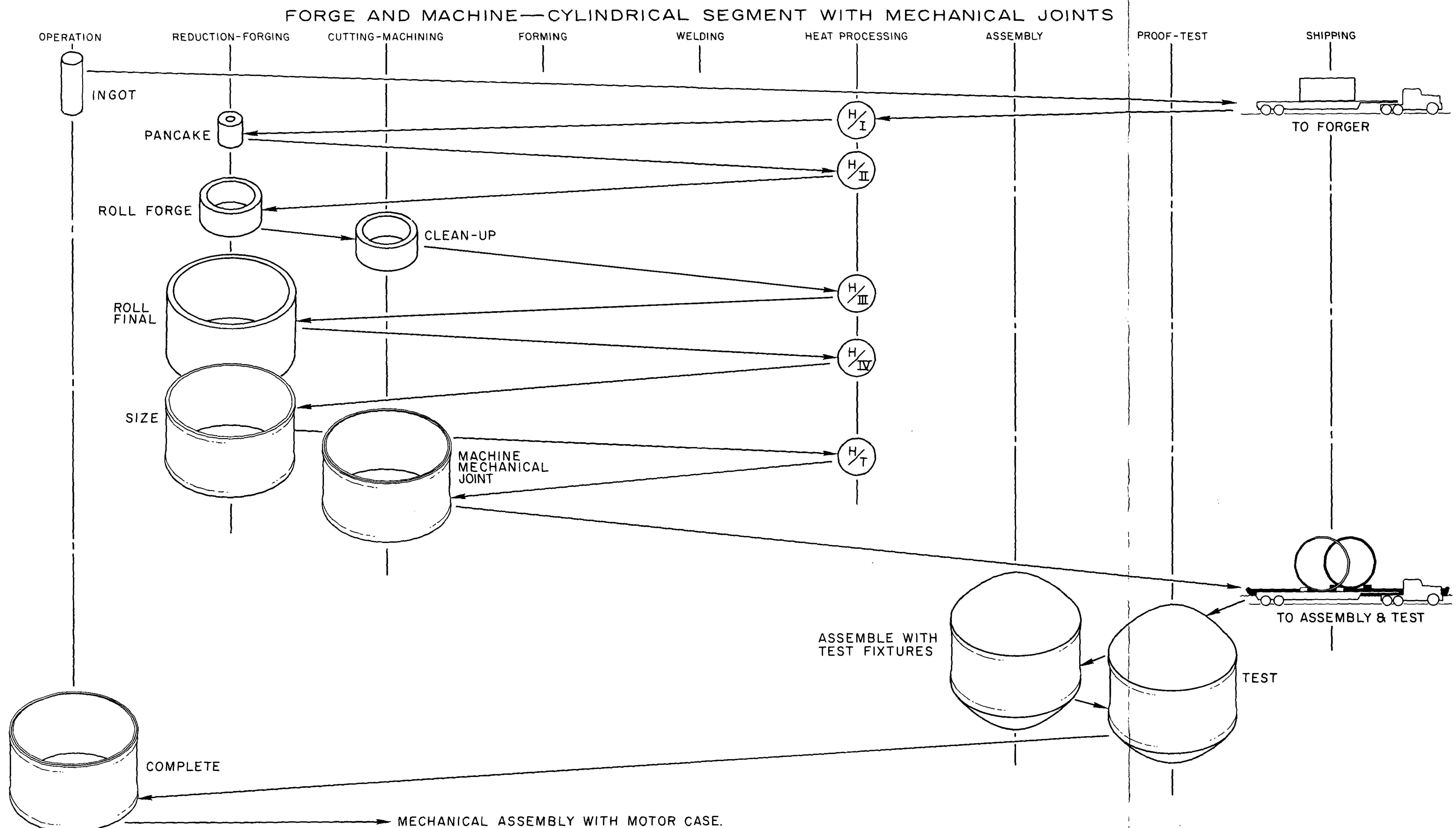

FIGURE 3

FORGE AND MACHINE — Y JOINT RING

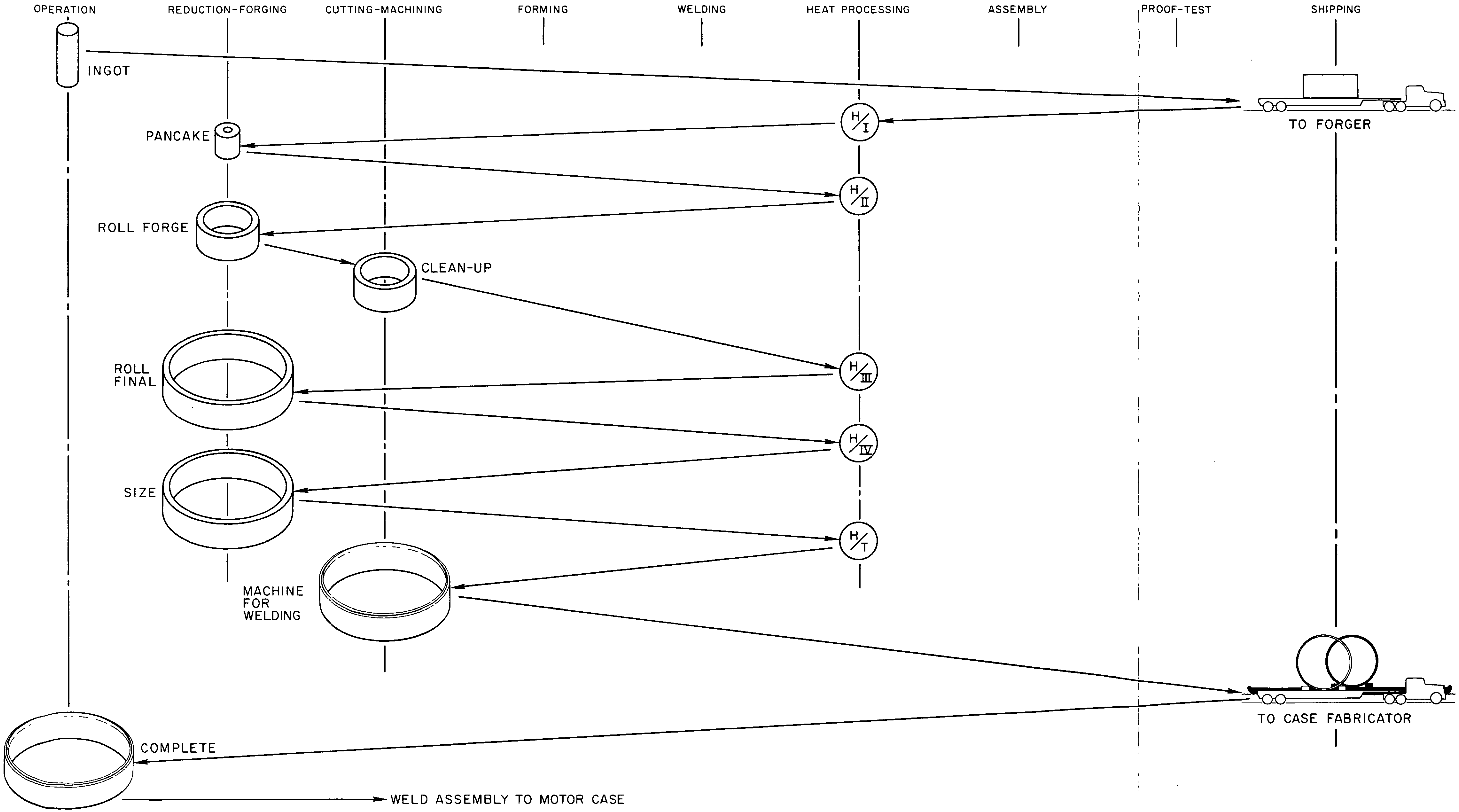

FIGURE 4

FORGE AND MACHINE PREFORM ROLL EXTENDED—CYLINDRICAL SECTION, MECHANICAL JOINTS

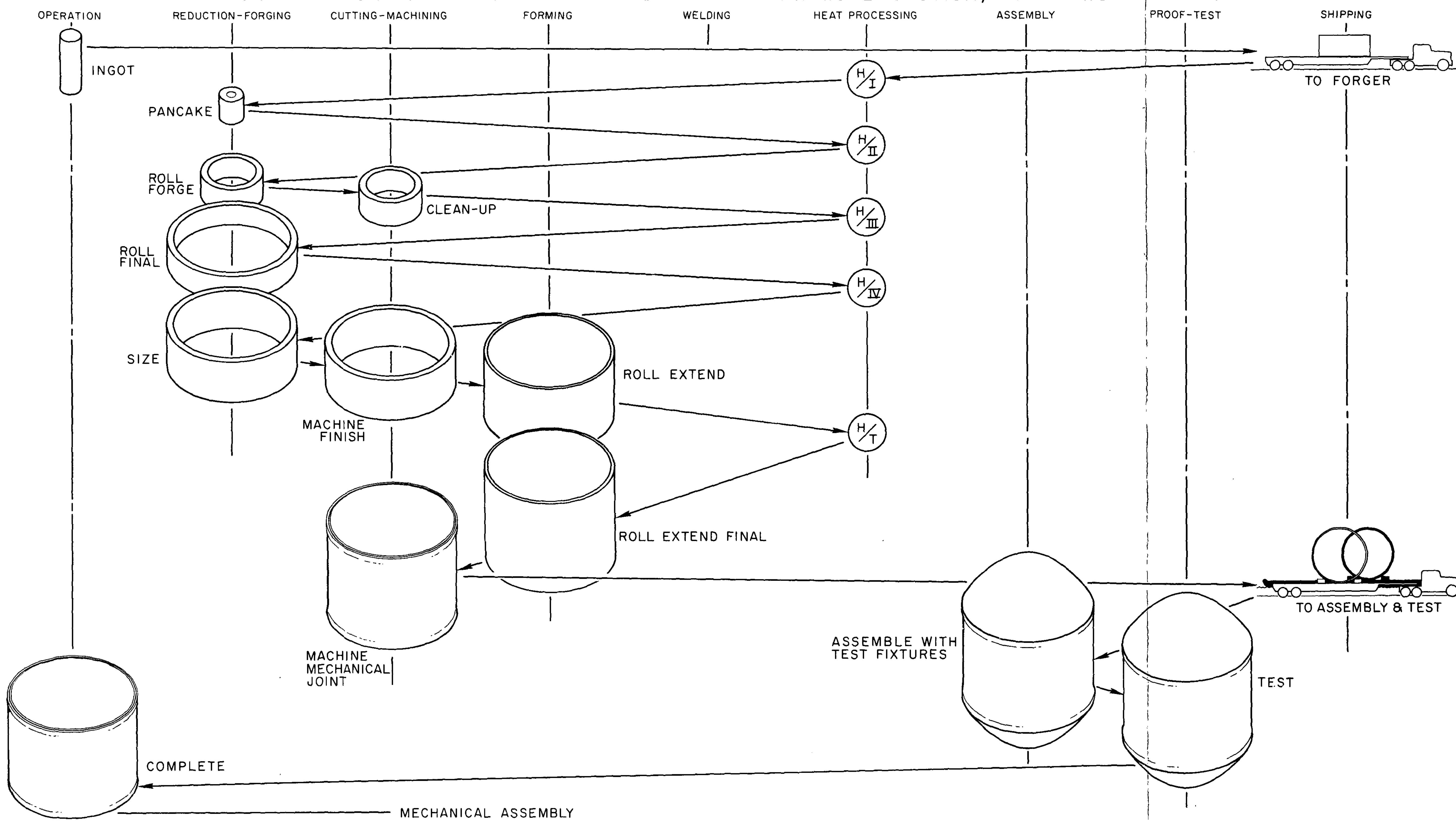

FIGURE 5

FOLDOUT FRAME

FOLDOUT FRAME

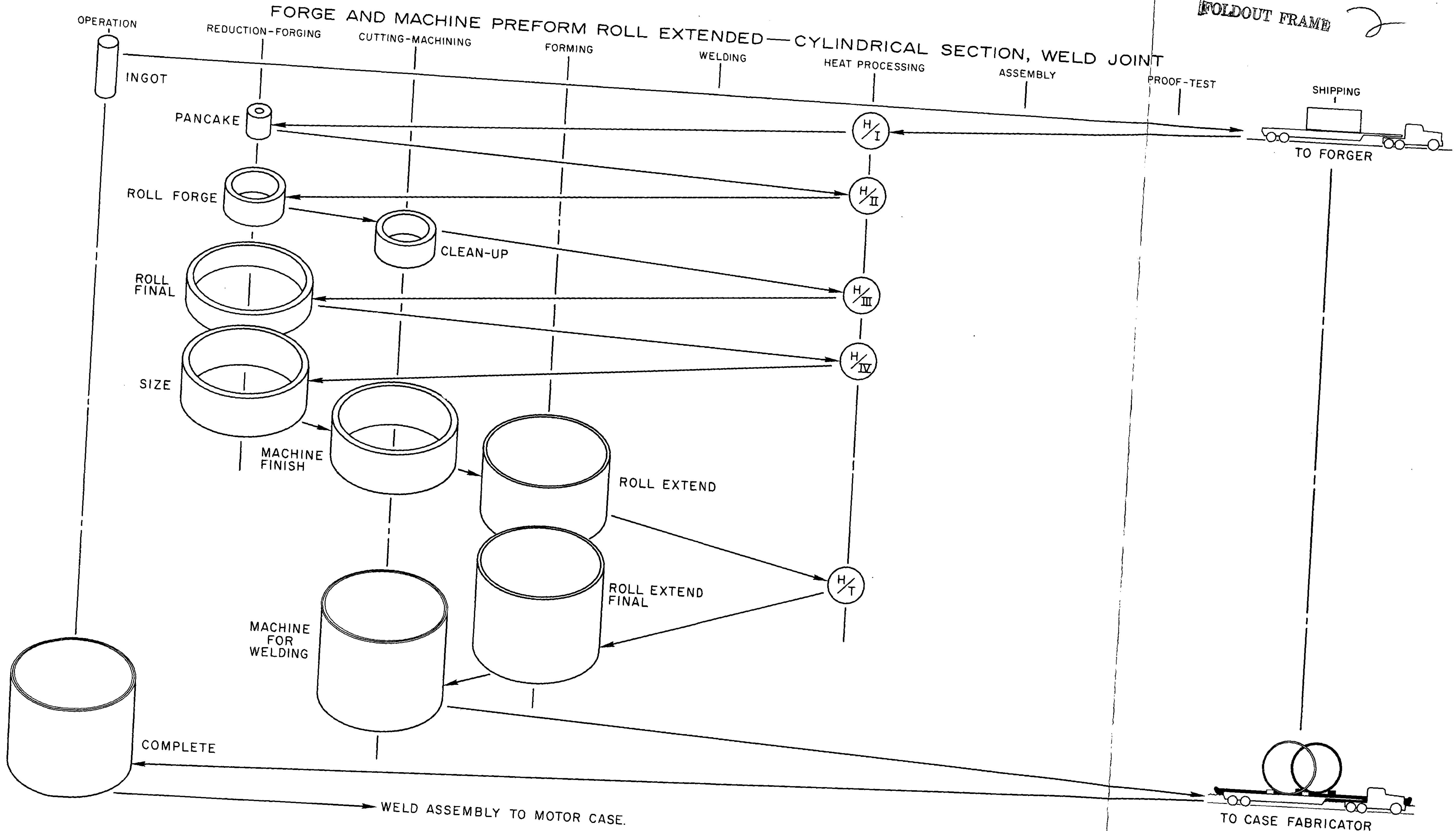

FIGURE 6

FOLDOUT FRAME 1

FOLDOUT FRAME 2

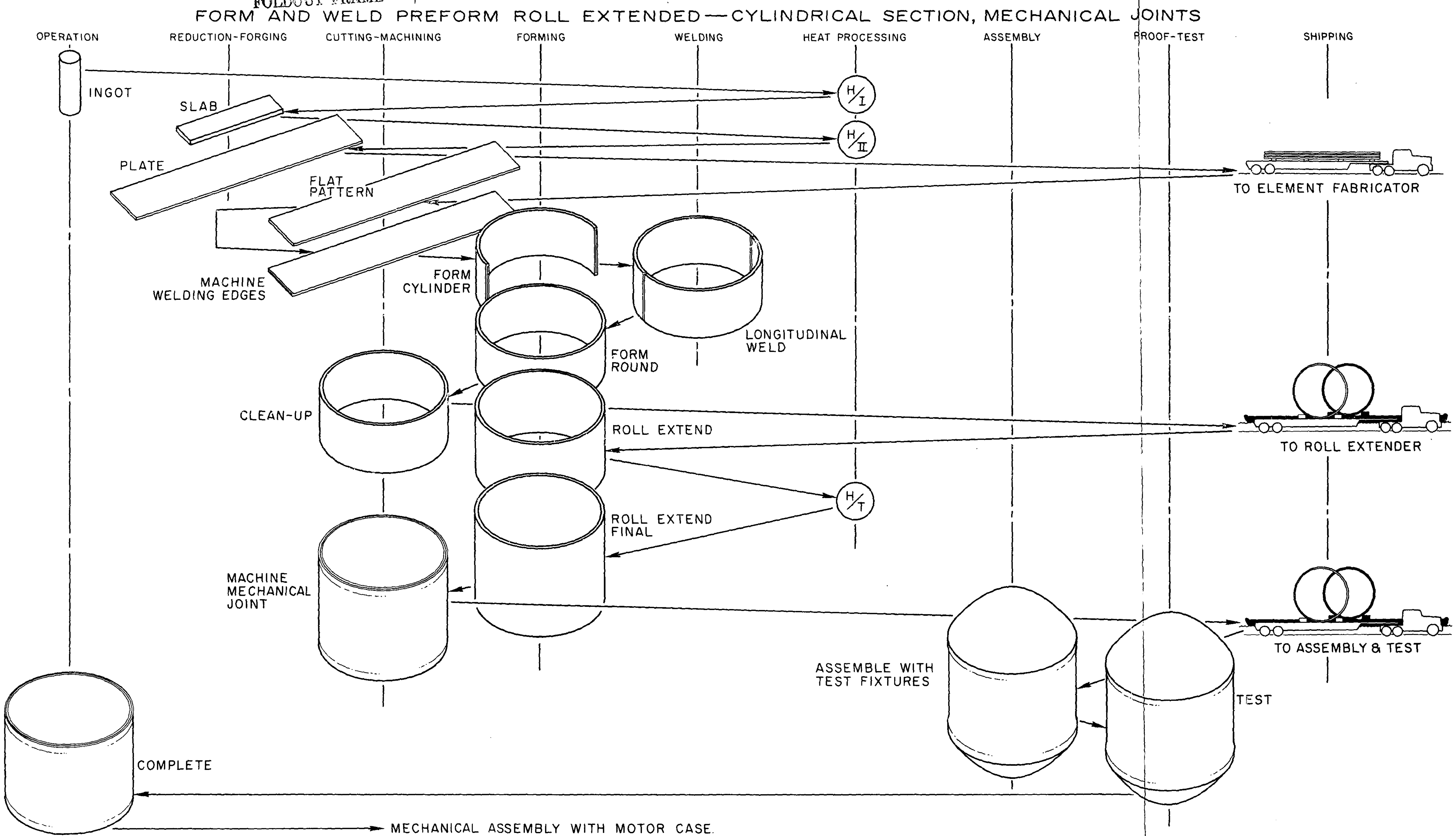

FIGURE 7

FOLDOUT FRAME

FOLDOUT FRAME

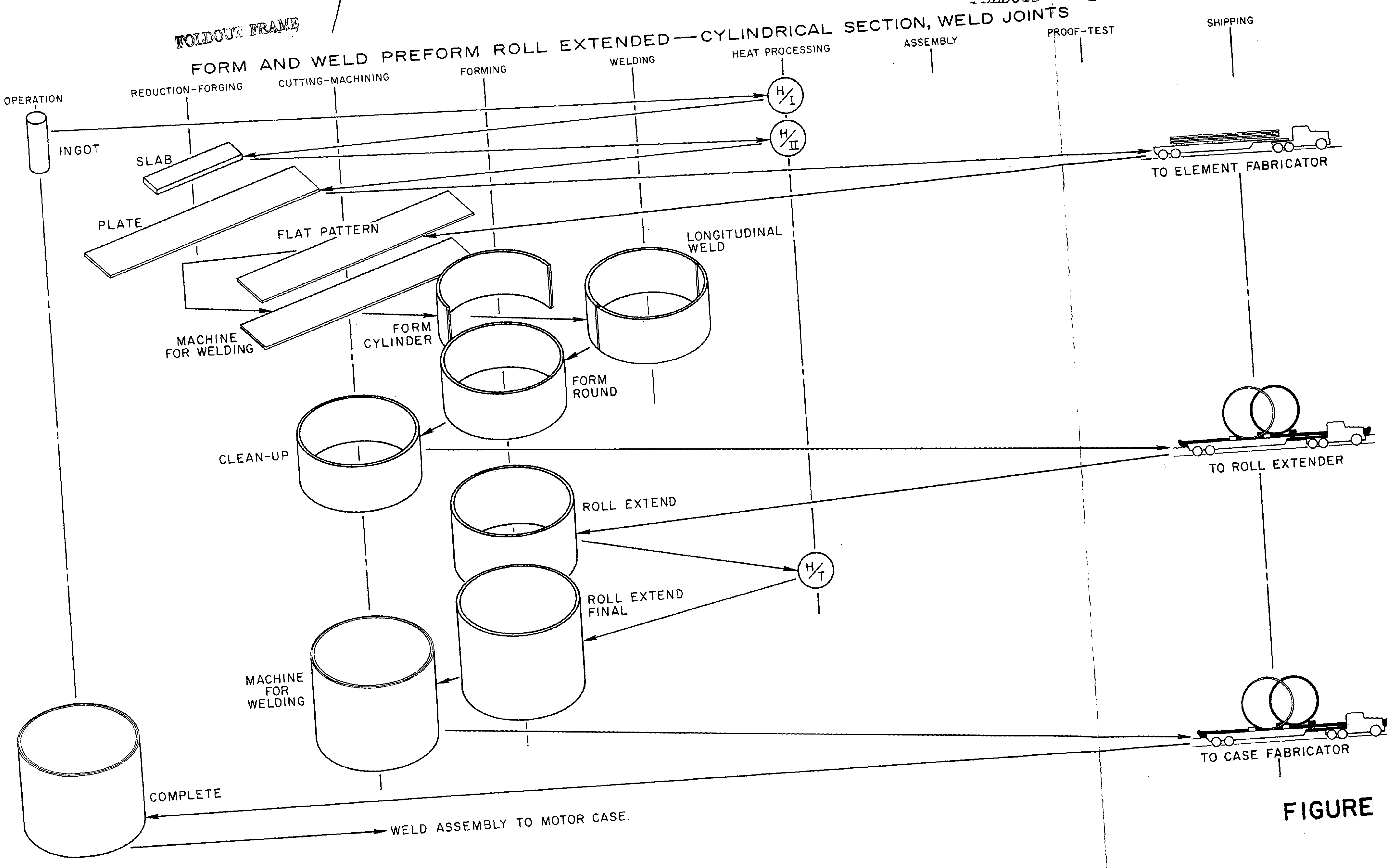

FIGURE 8

FOLDOUT FRAME

FOLDOUT FRAME 2

PRESS SPIN AND MACHINE—SPHERICAL SURFACE

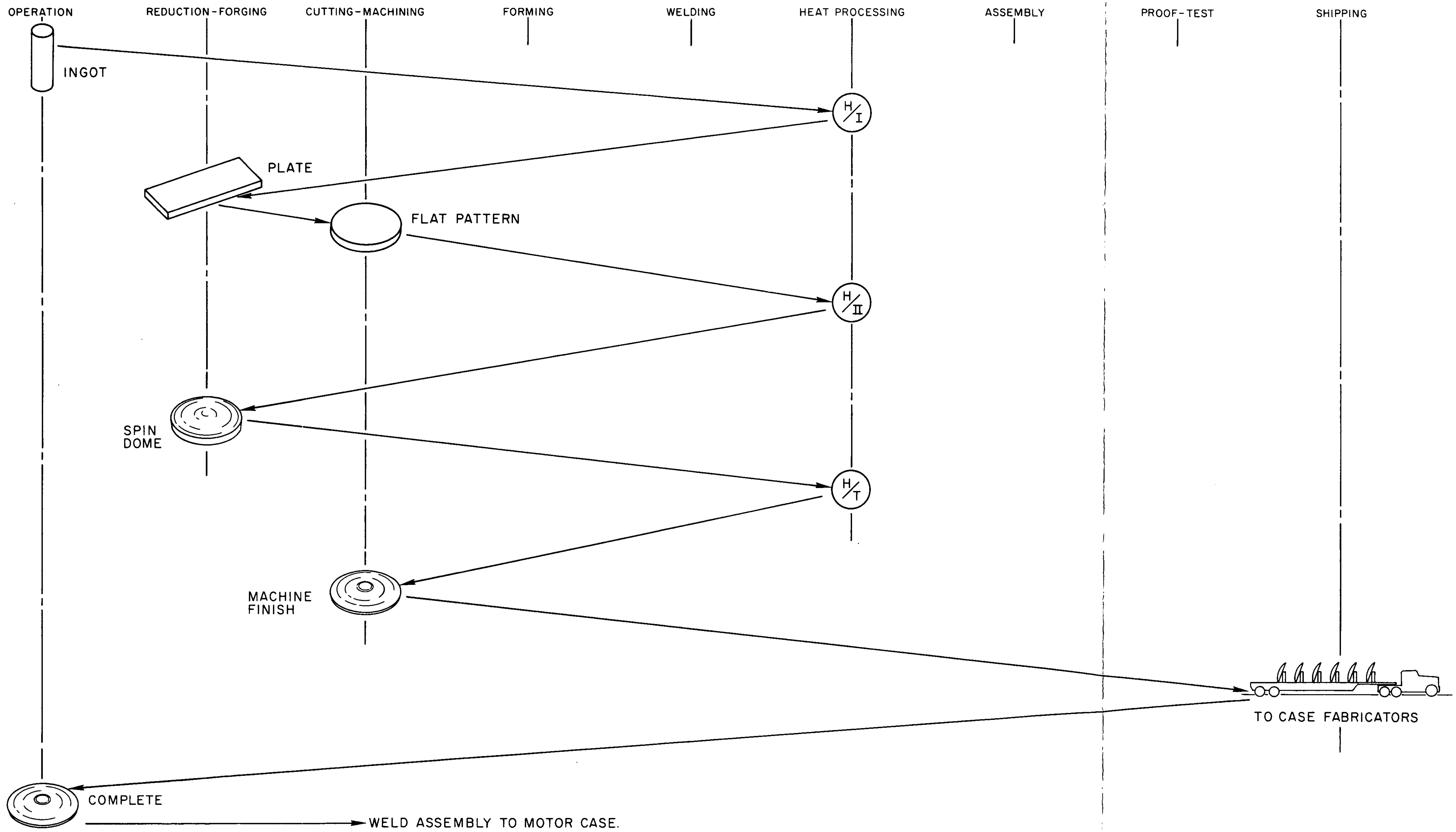

FIGURE 9

FOLDOUT FRAME 1

FOLDOUT FRAME 2

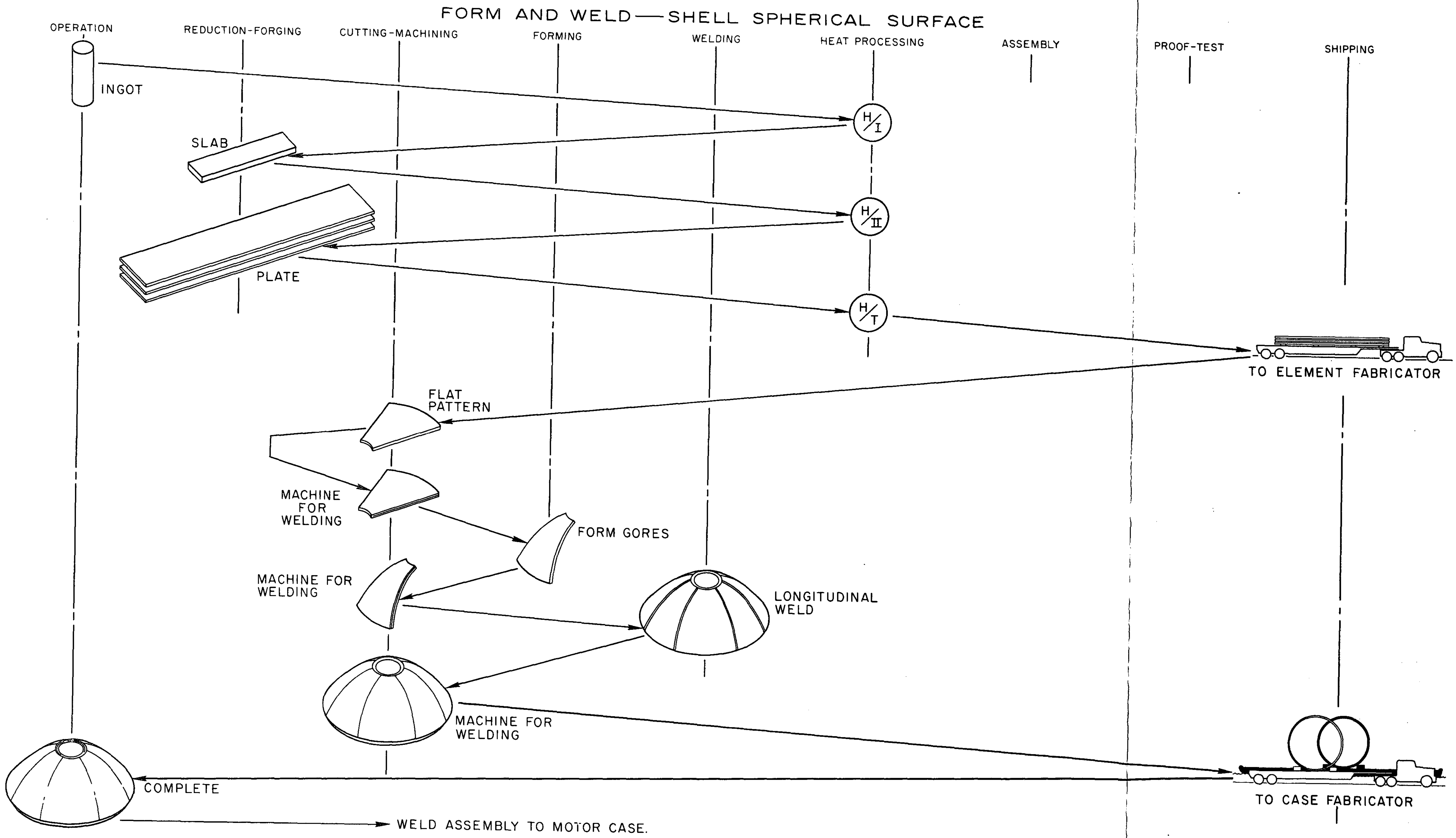

FIGURE 10