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EVALUATION OF ADVANCED REGENERATOR SYSTEMS

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SUMMARY

This report compares the advantages of different ceramic regenerator systems for an improved gas turbine engine in terms of cost, durability, and performance. Two ceramic materials (aluminum silicate and magnesium aluminum silicate), three fabrication methods (corrugating, embossing, and extruding), and three heat exchanger passage geometries (sinusoidal, rectangular, and isosceles triangular) have been evaluated for use in a 100hp automotive gas turbine at a regenerator inlet temperature of 1000°C (1832°F). To a great extent, this report is based on experience gained in the on going DOE-NASA/FORD regenerator development program.

Since the cost of the seals and drive were essentially identical for all cases studied, the core cost was the only variable affecting overall regenerator system cost. The cost of a ceramic core is primarily a function of the starting material and the material processing steps required prior to and after regenerator fabrication. It is in this area that magnesium aluminum silicate (MAS) provides a significant advantage over aluminum silicate (AS) due to the inherently simpler material processing required.

An automotive gas turbine regenerator would have a design life goal of 3500 hours (about 100,000 miles). Both AS and MAS regenerators appear to have the capability of meeting this minimum durability goal at a regenerator inlet temperature operating condition of 1000°C (1832°F). To date, neither material has shown the potential for operation above this temperature. The problems which have been manifested concerning these materials at temperatures above 1000°C (1832°F) are the high thermal expansion (and consequently high thermal stress) of MAS, and the thermal instability of AS.

The efficiency of a regenerative heat exchanger is a function of the heat transfer and flow friction characteristics of the matrix. These characteristics, which are determined (to a great extent) by the regenerator fabrication process, are a function of the configuration of the matrix flow passages and of the matrix wall thickness. A comparison of three process-flow geometry combination regenerators currently in various stages of development (corrugated-sinusoidal, embossed-rectangular, and extruded-isosceles triangular) indicate that the extruded isosceles triangular passage regenerator is potentially the most advantageous in terms of heat transfer performance characteristics. This fabrication process, however, requires the greatest technology development.

INTRODUCTION

Concern over motor vehicle exhaust emissions and the necessity for improved fuel economy have generated interest in alternatives to the traditional reciprocating spark ignition automotive powerplant. One alternative which invites close attention is the regenerative gas turbine. With these concerns of emissions and fuel economy in mind, the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA), in conjunction with the automotive industry, have embarked on a program to provide the automotive industry with the option of initiating production engineering development of an improved gas turbine engine system in the 1983 to '85 time frame. An improved gas turbine system has been defined by NASA as one which incorporates "existing or near-term technology, has at least a twenty percent gain in fuel economy over current spark ignition engines, and compares favorably with respect to noise, driveability, reliability and life-cycle costs" (Reference 1). Of course, the improved gas turbine must also meet the most stringent mandated emission requirements.

Of critical importance to the success of the development of the improved gas turbine is the development of an efficient, reliable, and low-cost heat exchanger. Because the efficiency of a gas turbine engine is directly related to the temperature difference between inlet air to the compressor and exhaust gas from the turbine, the improved gas turbine, to be competitive, will operate at turbine inlet temperatures of up to 1150°C (2100°F). This will result in heat exchanger inlet temperatures approaching 1000°C (1832°F). These operating temperatures dictate the use of a ceramic heat exchanger.

Since 1965, Ford Motor Company has been engaged in the development of ceramic regenerator systems for use in gas turbine engines. This development effort has focussed on three ceramic matrix materials for the regenerator application. Prior to 1974, over 100,000 hours of engine operating experience were accumulated on a sample of approximately 1000 regenerator cores fabricated from lithium aluminum silicate (LAS) culminating in the determination that this material is not suitable for regenerator service due to a propensity for failure resulting from chemical attack from sodium or sulfur encountered in common road salt and diesel fuel respectively. In 1974, two ceramic materials, aluminum silicate (AS) and magnesium aluminum silicate (MAS), were screened in laboratory tests. As a result, these materials were considered to have acceptable resistance to chemical attack. Regenerator cores made from these materials were placed on engine durability test in late 1974 and early in 1975.

Late in 1974, the Alternate Automotive Power Systems Division of the Environmental Protection Agency joined Ford Motor Company in an "Automotive Gas Turbine Ceramic Regenerator Design and Reliability Program" with the specific objective of achieving a regenerator life of 10,000 hours on a truck/industrial gas turbine engine duty cycle at a regenerator inlet temperature of 800°C (1472°F). This testing has been carried out using the Ford 707 gas turbine engine. In 1975, this program was transferred to the Energy Research and Development Agency (ERDA) and, when the ERDA/FORD contract was completed in September of 1976, NASA was given technical and administrative responsibility for this program under the auspices of the Department of Energy (DOE).

This report will examine and compare the advantages of AS and MAS regenerators incorporating different geometries and manufacturing processes for use in a 100hp gas turbine engine relative to cost, efficiency, and durability. These comparisons will, to a great extent, be based on experience gained in the NASA/FORD regenerator development program. Each of these equally important criteria (cost, durability, and performance) is a function of the manufacturing process used to fabricate the regenerator. In addition, cost and durability are functions of the ceramic material from which the regenerator is made.

A general discussion of materials, manufacturing processes, and aerothermodynamic performance, and the relationship of these factors to the criteria of cost, performance, and durability comprise the first four sections of this report. An attempt is made to estimate the improvements in these factors which might be expected due to technological advances over the next five to ten years. In the final sections of this report, three specific process and material combinations are studied:

1. An AS regenerator incorporating a sinusoidal flow passage made from a corrugated wet paper process.
2. An MAS regenerator incorporating a rectangular flow passage formed by an embossing process, and
3. An MAS regenerator incorporating an isosceles triangular flow passage formed by extrusion.

A heat exchanger made from each of these configurations is designed for operation at 1000°C (1832°F) in a 100hp automotive gas turbine and a comparison of cost, durability, and performance (as well as package size) is made. The ceramic core for this application will be about 36 cm. (14 in.) in diameter.

DISCUSSION OF RESULTS

1.0 MATERIAL COMPARISON

Since 1974, Ford has accumulated considerable engine test experience on both AS and MAS regenerators at a regenerator inlet temperature of 800°C (1472°F) using the Ford 707 industrial gas turbine as a test bed (Reference 2). Over 50,000 core hours of durability test on AS regenerators, with no core failures due to chemical attack (from sodium or sulfur encountered in common road salt or diesel fuel respectively) or thermal stress, demonstrate the suitability of AS for this heat exchanger application. MAS regenerators, properly designed to account for their inherently higher thermal expansion (and consequently higher thermal stress) have also operated successfully at this temperature and must also be considered useful at this operating condition.

Since it has been determined that transient thermal stresses in the regenerator core are no more severe than those encountered during steady state operation (Reference 3), these durability test results encourage a high confidence of successful operation in an automotive application where considerably more transient operation would be expected.

Also, for the automotive application, a life of 3500 hours would be acceptable. In the 800°C (1472°F) durability tests at Ford, twelve AS regenerators and one MAS regenerator have survived over 3000 hours of operation, and five of these AS cores have operated for over 7000 hours.

For either AS or MAS to be considered viable for use in future gas turbine engines, higher operating temperature capability must be assured. DOE and NASA have specified as a second goal in the gas turbine engine development program the definition of an advanced gas turbine by the mid 1980's along with the necessary technology development such that production is possible in the 1990's. An advanced engine is defined as one which "incorporates significant advances in technology, and has a fifty to sixty percent gain in fuel economy over the spark ignition engine of 1976 while meeting the same goals of emissions, driveability, etc. as the improved gas turbine engine" (Reference 1). For the improved gas turbine of this discussion, the regenerator inlet temperature is considered to be 1000°C (1832°F), but consistent with the development of the advanced engine, this temperature can reasonably be expected to increase to 1100°C (2012°F) or 1200°C (2192°F) by the 1990's.

In consideration of the high temperature requirements for future heat exchangers, three Ford 707 engines have been specially modified to provide regenerator durability data at elevated temperature operating conditions. Four AS regenerators have accumulated a total of over 12000 hours of durability test in these engines at average inlet temperatures of 982°C (1800°F), and two of these cores have each operated for over 3500 hours. This regenerator inlet temperature is obtained by operating the engine at turbine inlet temperatures of 1065 to 1080°C (1950 to 1975°F) at 60 to 65% gasifier spool speed and low power turbine speed. The four cores thus far show no evidence of damage due to thermal stress or chemical attack. More hours on a bigger sample of the AS cores must be generated before any statistically significant conclusions can be made about the achievement of durability goals for this material at 1000°C (1832°F).

Although MAS regenerators have not been operated at this elevated temperature for long periods of time, analysis presented in Reference 2 predicts that MAS is capable of such operation and, indeed, this prediction will be verified by engine test. There are, however, certain difficulties unique to higher thermal expansion ceramics such as MAS which are encountered when designing a heat exchanger for high temperature conditions.

The operating environment of a gas turbine engine regenerator consists of high temperature turbine exhaust gas passing through the core, and low temperature compressor discharge air surrounding the regenerator rim. The resulting thermal constraint at the rim due to the gradient across the peripheral seal subjects the core to tangential tensile stress within the seal width at the regenerator hot face. For MAS materials, the tensile stress at the periphery may be severe enough to generate cracks at that location. By slotting the rim (Figure 1), the tangential stress at the hot face outer diameter can be significantly reduced and successful elevated temperature operation is possible. The geometry and number of the stress relief slots incorporated, as well as the physical properties of the MAS core, dictate the increase in operating temperature which may be accommodated.

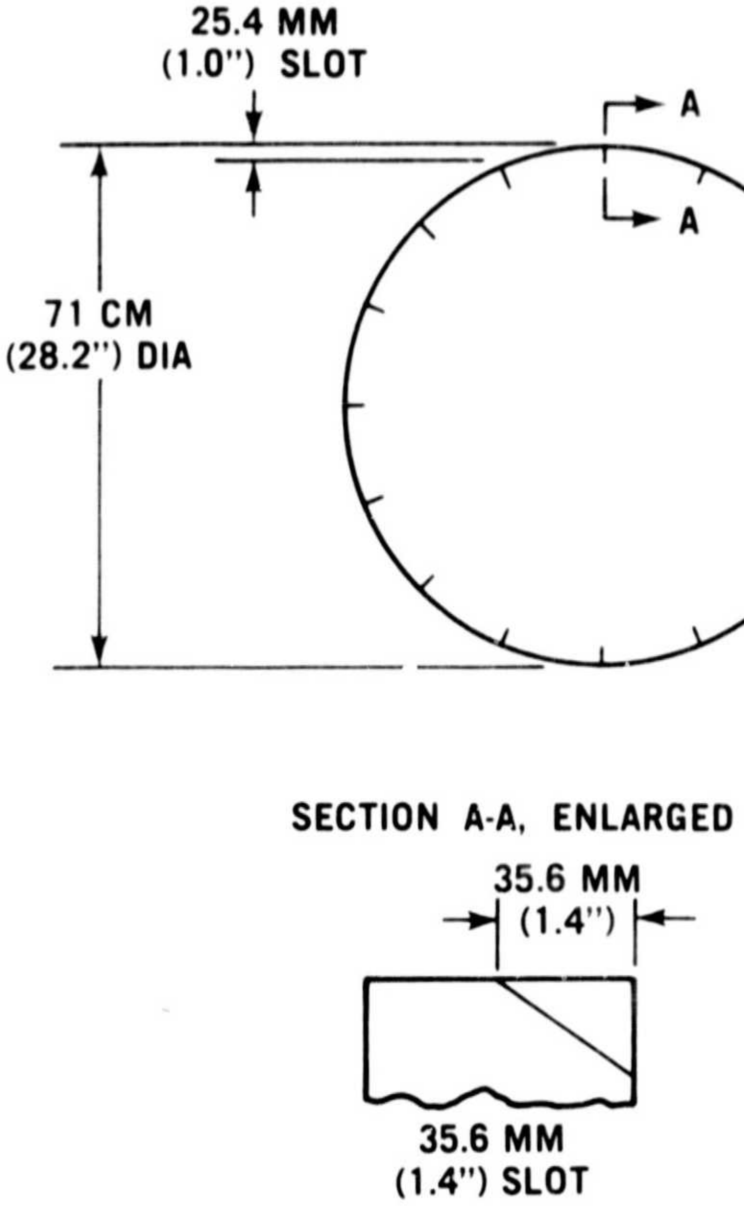


Figure 1 Slotted Rim Designs

Although slotting the rim of an MAS regenerator can serve to increase the operating temperature capability, there must come a point at which a regenerator can accommodate no more stress relief without drastically affecting the structural integrity of the rim and causing failures in the field. Indeed, MAS regenerators have been engine evaluated for long periods of time only at an inlet temperature of 800°C (1472°F) even though analysis predicts successful operation at 1000°C (1832°F) in an improved gas turbine application. The eventual solution to operation of MAS regenerators at temperatures above 1000°C (1832°F) for an advanced gas turbine application must be to develop a lower thermal expansion material.

A number of studies have been carried out both at Ford and by manufacturers of MAS matrices to determine the lower limit of thermal expansion of MAS. It has been shown that the thermal expansion of this material can be lowered significantly by heat treatment to vary the amount of glass in the ceramic composition and, by extrapolative techniques, a minimum thermal expansion of 1160 ppm at 800°C (1472°F) has been estimated (Reference 4). More recently, the theoretical lower limit of thermal expansion of MAS was demonstrated by X-ray diffraction measurement techniques of unit cell expansions to be 700 ppm at 800°C (1472°F) and 1300 ppm at 1000°C (1832°F) (Reference 5). These values of thermal expansion, in conjunction with adequate matrix strength and appropriate stress relieving would be acceptable for the advanced automotive gas turbine regenerator application at temperatures greater than 1000°C (1832°F). Thermal expansions below the theoretical lower limit can be attained by appropriate heat treatment to provide controlled microcracking (Reference 6). Microcracking, however, provides lower thermal expansion at the expense of strength. It would appear that although current MAS materials are limited to operation at 1000°C (1832°F) because of thermal stress, with development this material has the potential for operation at higher temperatures.

In addition to laboratory screening tests for thermal expansion, physical stability tests are being carried out to evaluate the operational capability of candidate ceramic matrix materials at temperatures of 1000°C (1832°F), 1100°C (2012°F), and 1200°C (2192°F). The physical stability tests are designed to measure the reaction of candidates to extended periods of time at elevated temperatures with and without the presence of corrosive elements (sodium and sulfur) which would exist in an engine environment from road or sea salt and diesel fuel respectively.

The physical stability of the MAS materials tested appears to be good, with no material showing a dimensional change of greater than 100 ppm after more than 800 hours of 1000°C (1832°F) exposure (Figure 2). Dimensional stability at elevated temperatures in the presence of corrosive agents (sodium and sulfur) is also very good.

It would seem then, that the operational temperature limit of MAS will be contingent upon striking a compromise between strength and expansion as material development continues and, once such matrices have been fabricated, on close attention to the mechanical design of the regenerator to reduce stress.

The problem concerning AS which has been identified in laboratory tests is its apparent unstable shrinkage at temperatures above 1000°C (1832°F); and even at this temperature a thermally induced dimensional change of 500 ppm occurs (Figure 2). This dimensional change is even greater (600 ppm) with sodium present. Recently, tests of the AS materials were suspended at 1100°C (2012°F) and 1200°C (2192°F) because, at these temperatures, the materials have developed visible cracks. It should be emphasized that these materials were fabricated for the 800°C (1472°F) application, not with the intention that they should provide service at such elevated temperatures. Extensive engine tests show that current AS materials are capable of prolonged operation at 1000°C (1832°F) and it is believed that more advanced versions of AS material will have higher temperature capability.

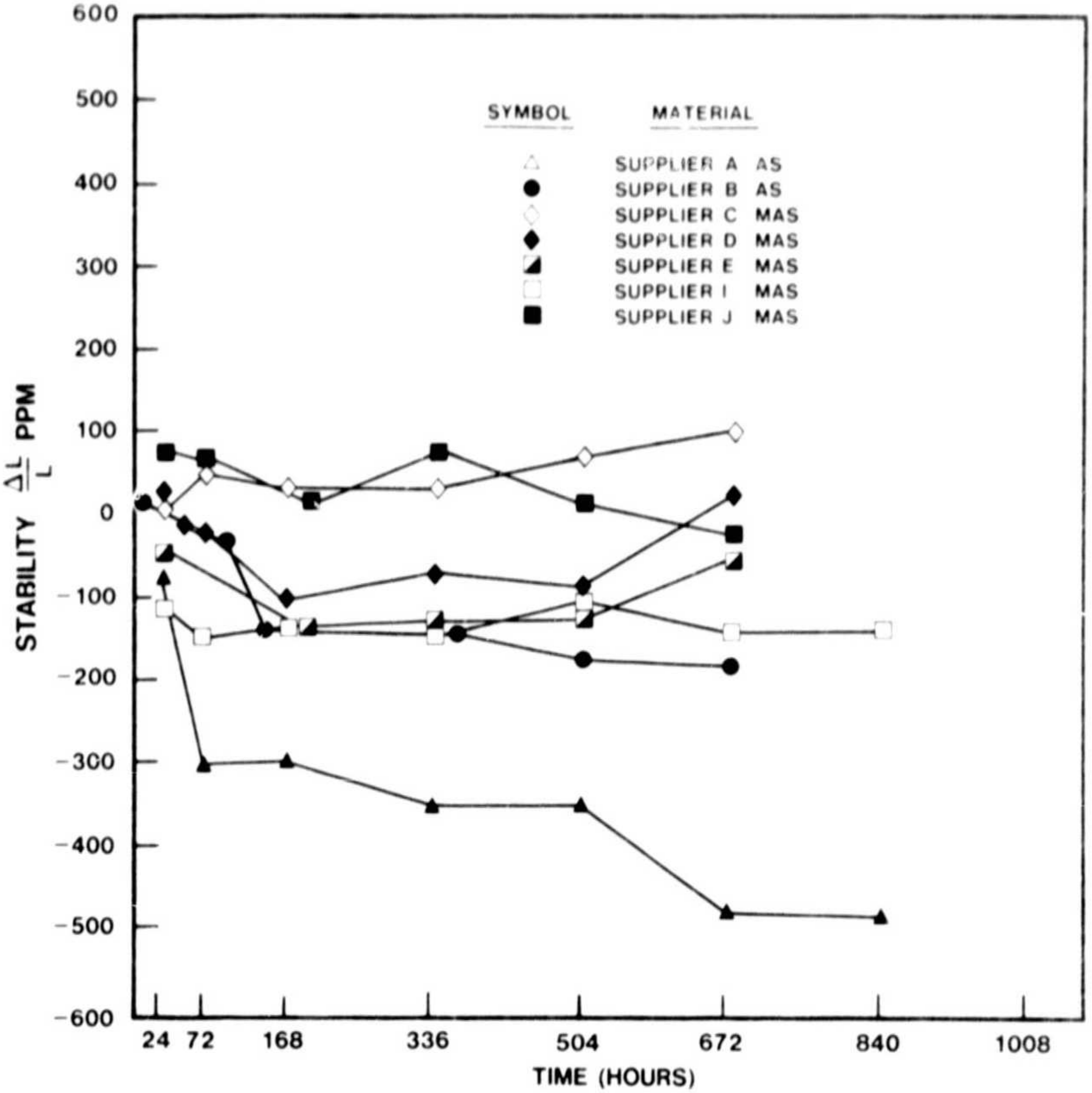


Figure 2 Thermal Stability of AS and MAS at 1000°C (1832°F)

A factor other than thermal stress and physical stability which must be considered when evaluating AS and MAS matrices for a regenerator application is resistance to mechanical stresses imposed by the drive and mounting system, or which may be encountered during the assembly procedure or by handling. The capability of a regenerator to withstand such stresses must be evaluated by considering the overall structural integrity of the matrix and the type and magnitude of loads to which it will be exposed. This is of particular importance when considering that the direction in matrix fabrication must be toward thinner wall (and therefore, weaker) structures to provide more effective heat transfer.

Although no rigorous analytical or experimental investigations have been undertaken, one may speculate as to the comparitive strengths of equivalent wall thickness and geometry AS and MAS matrices. For example, the solid bar modulus of rupture (MOR) of the lithium aluminum silicate (LAS) reference material is on the order of 68,900 Kpa (10,000 psi) and, based on materials tests conducted at Ford, a ratio of approximately 10 to 1 exists between the solid bar MOR and the LAS matrix tangential MOR. The AS (lithium-leached LAS) matrix with the same wall thickness and geometry exhibits an average tangential MOR of about 4823 Kpa (700 psi). If the 10 to 1 ratio is valid, this would indicate a "solid bar" strength of 48,230 Kpa (7000 psi). A wide range of solid bar MOR strengths have been reported for different MAS materials (Reference 7, 8), some of which are equivalent to or greater than that of LAS which may indicate that a strength advantage is available for MAS over AS regenerators with the same wall thickness and geometry.

In summary, the problems which have manifested themselves in the course of laboratory and engine durability tests concerning AS and MAS at the elevated temperatures required for the improved or advanced gas turbine are:

1. The high thermal expansion of MAS, which could cause thermal cracks and core failure.
2. The fact that AS appears to be thermally unstable and shrinking at temperatures above 1000°C (1832°F), and this also could cause cracks and a core failure.

Continued materials development, in concert with careful regenerator mechanical design, is required to provide operational capability for these materials at regenerator inlet temperatures above 1000°C (1832°F).

2.0 COMPARISON OF FABRICATION METHODS

A variety of regenerator manufacturing processes, materials, and flow passage geometries are available as the result of several different manufacturers engaging in the fabrication of ceramic cellular structures. Each manufacturer has selected a process and material that is compatible with his experience and facilities. In fabricating a ceramic matrix, the ceramic material strength and process limitations usually dictate a matrix wall thickness and flow passage geometry. As a result, each manufacturer has developed a ceramic material, passage geometry, and process that is different from the others and which has certain advantages or limitations to performance, durability, or cost when compared to the others.

The three manufacturing processes currently available for fabricating ceramic cellular structures for rotary heat exchanger applications are:

1. Corrugating
2. Embossing
3. Extrusion

2.A CORRUGATING — The process of corrugating from a wet paper or plastic binder carrier (Figure 3) dates back to the early 1950's and has been well developed. This process produces a sinusoidal flow passage by winding alternate layers of corrugated and flat sheets, and has yielded matrices with wall thicknesses as low as 0.06 mm (0.0025 in). Ceramic regenerators made from AS material have been fabricated with this process in sizes up to 717 mm (28.25 in) diameter with 0.06 mm (0.0025 in) wall thicknesses and have been on durability test in the Ford 707 engine for two years. They have accumulated 7000 hours at 800°C (1472°F) and 3000 hours at 982°C (1800°F) with little or no distress (Reference 2).

For this type of structure, variations in corrugating roll pressure, winding tension, and shrinkage during firing can produce significant discrepancies in cell geometry in a given matrix (Figure 4). Performance tests conducted in the course of the NASA/FORD regenerator development program have shown that non-uniformity in cell structure can result in a serious performance loss (Reference 2). This non-uniformity can be minimized somewhat by reducing the aspect ratio (the ratio of passage corrugation width to height), and the radius of curvature imparted by the corrugating rolls.

Although the corrugating process is well developed, additional reductions in wall thickness below 0.06 mm (0.0025 in) and improvements in cell uniformity are still possible. The disadvantages of this process are that the use of non-recoverable paper has an associated cost penalty and, as will be discussed later, the sinusoidal flow passage is not the most desirable in terms of performance.

2.B EMBOSSING — This process consists of forming ribbed tape by either extruding or calendaring a flat ceramic sheet which is then embossed and wrapped around a mandrel to produce a rectangular passage regenerator (Figure 5). The advantages to this process are a potential high speed, single sheet operation with no paper carrier, easy re-use of scrap material, and desirable performance characteristics associated with rectangular matrix passages. Although the capability of making a regenerator matrix with sheet less than 0.15 mm (0.006 in.) thick has yet to be demonstrated, the technology is progressing rapidly and small matrix samples have already been wound with a sheet thickness of 0.10 mm (0.004 in.) and a rib thickness of 0.18 mm (0.007 in.).

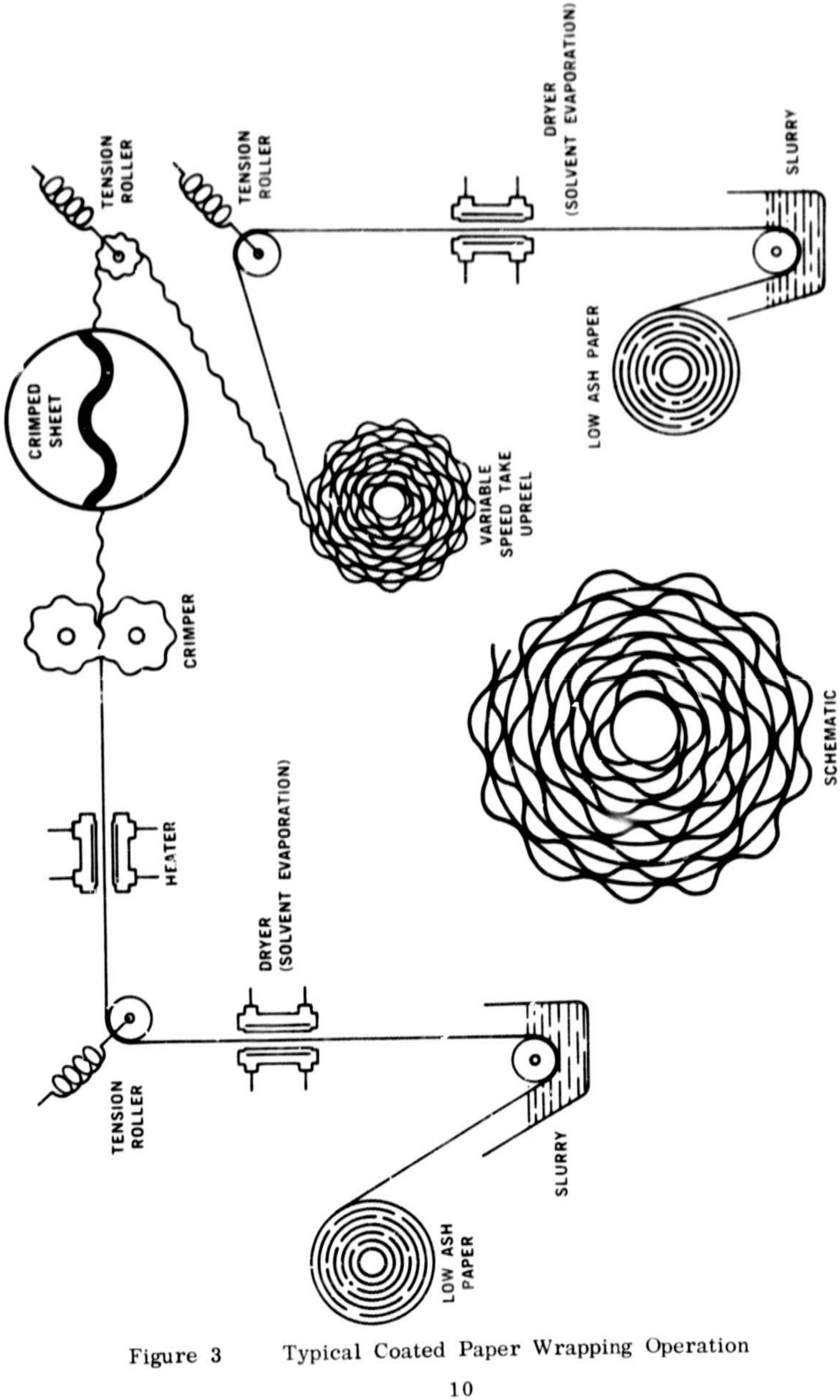
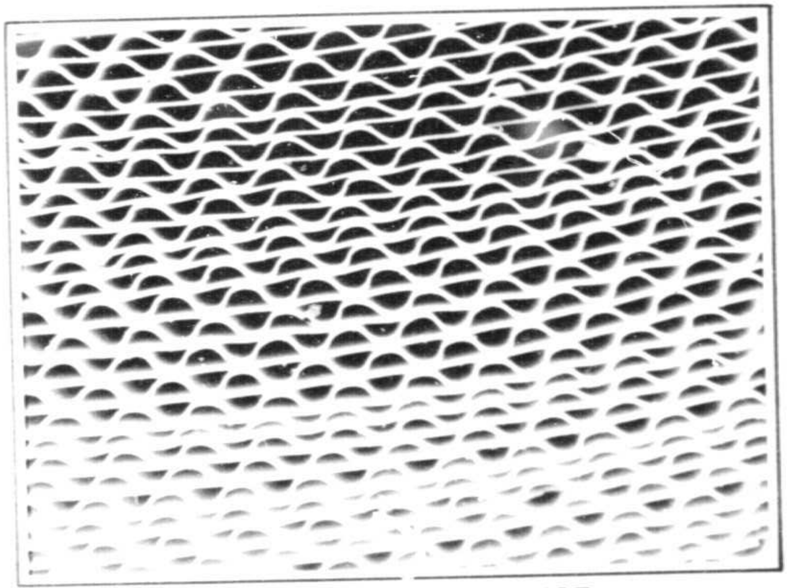
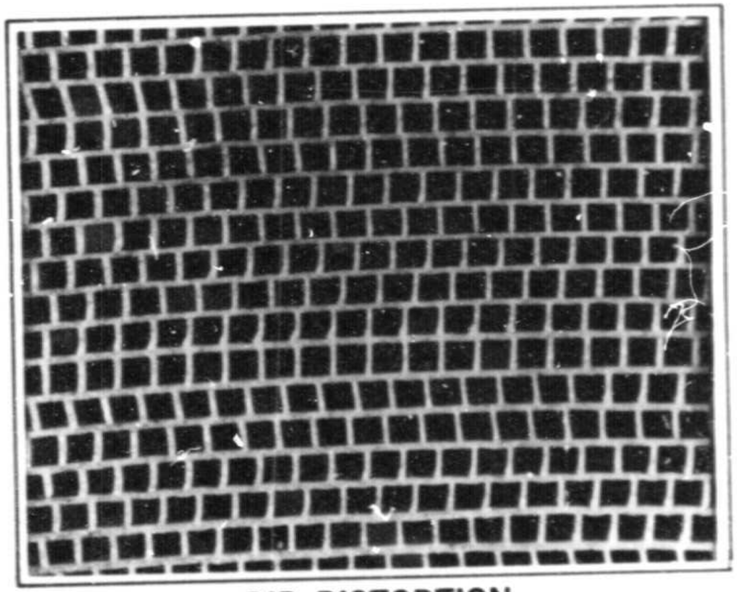


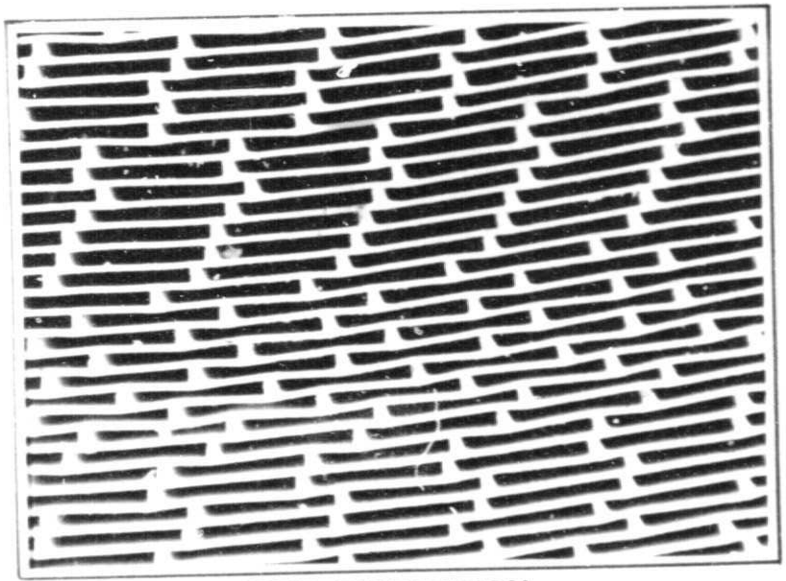
Figure 3 Typical Coated Paper Wrapping Operation



FIN HEIGHT VARIANCE



RIB DISTORTION



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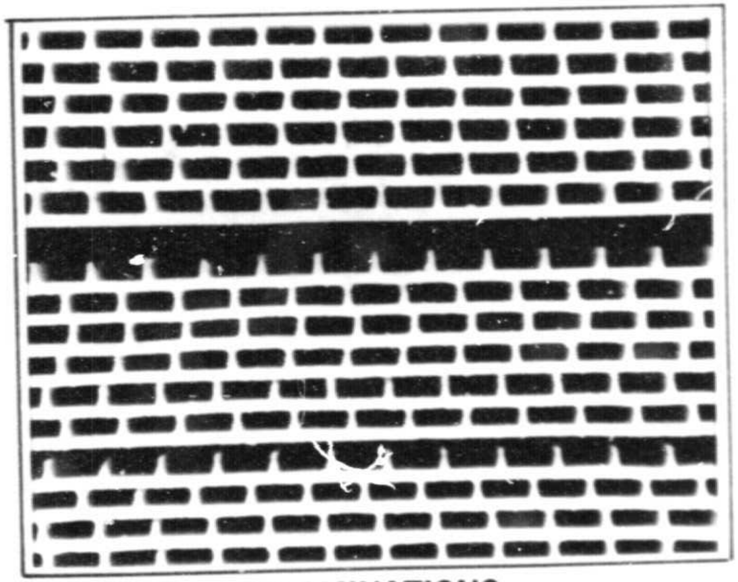
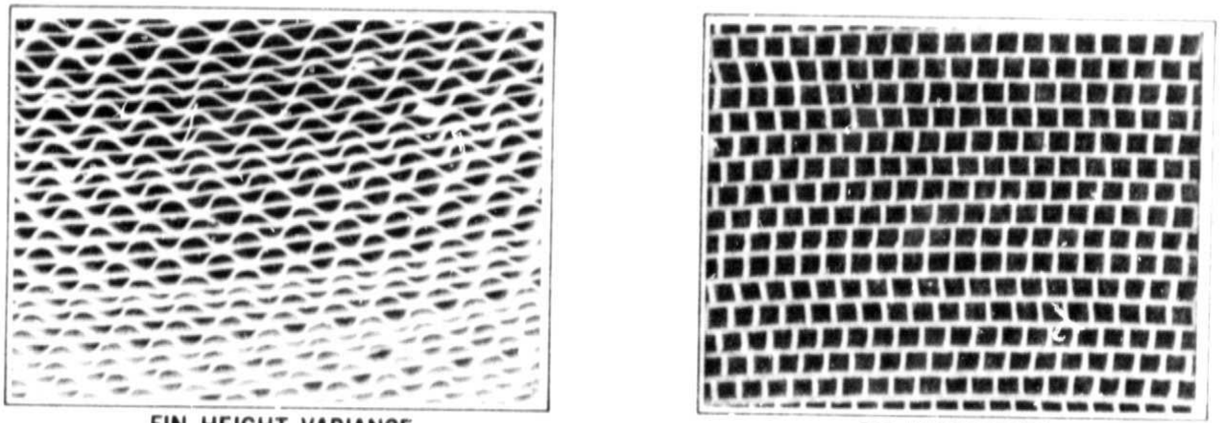
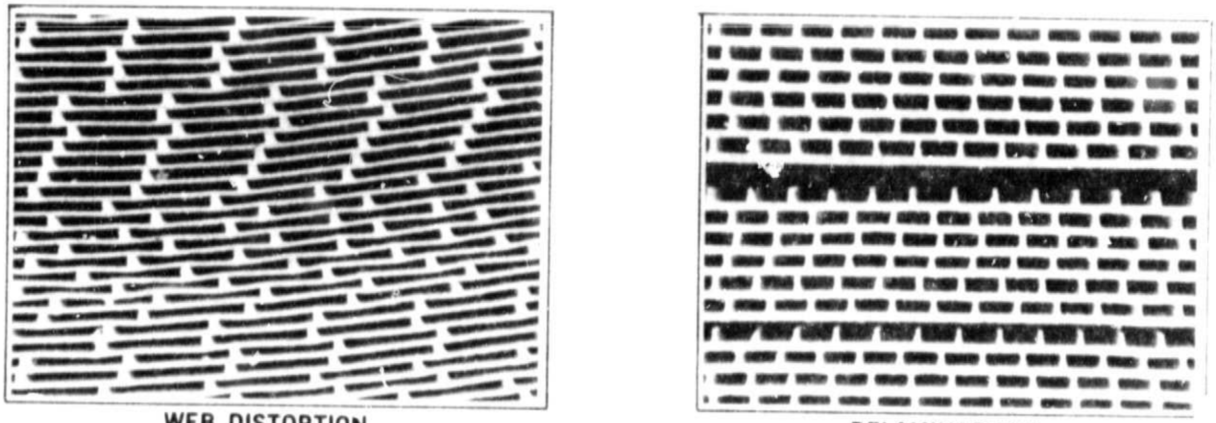


DELAMINATIONS



FIN HEIGHT VARIANCE

RIB DISTORTION



WEB DISTORTION

DELAMINATIONS

Figure 4 Photographs illustrating Manufacturing Defects

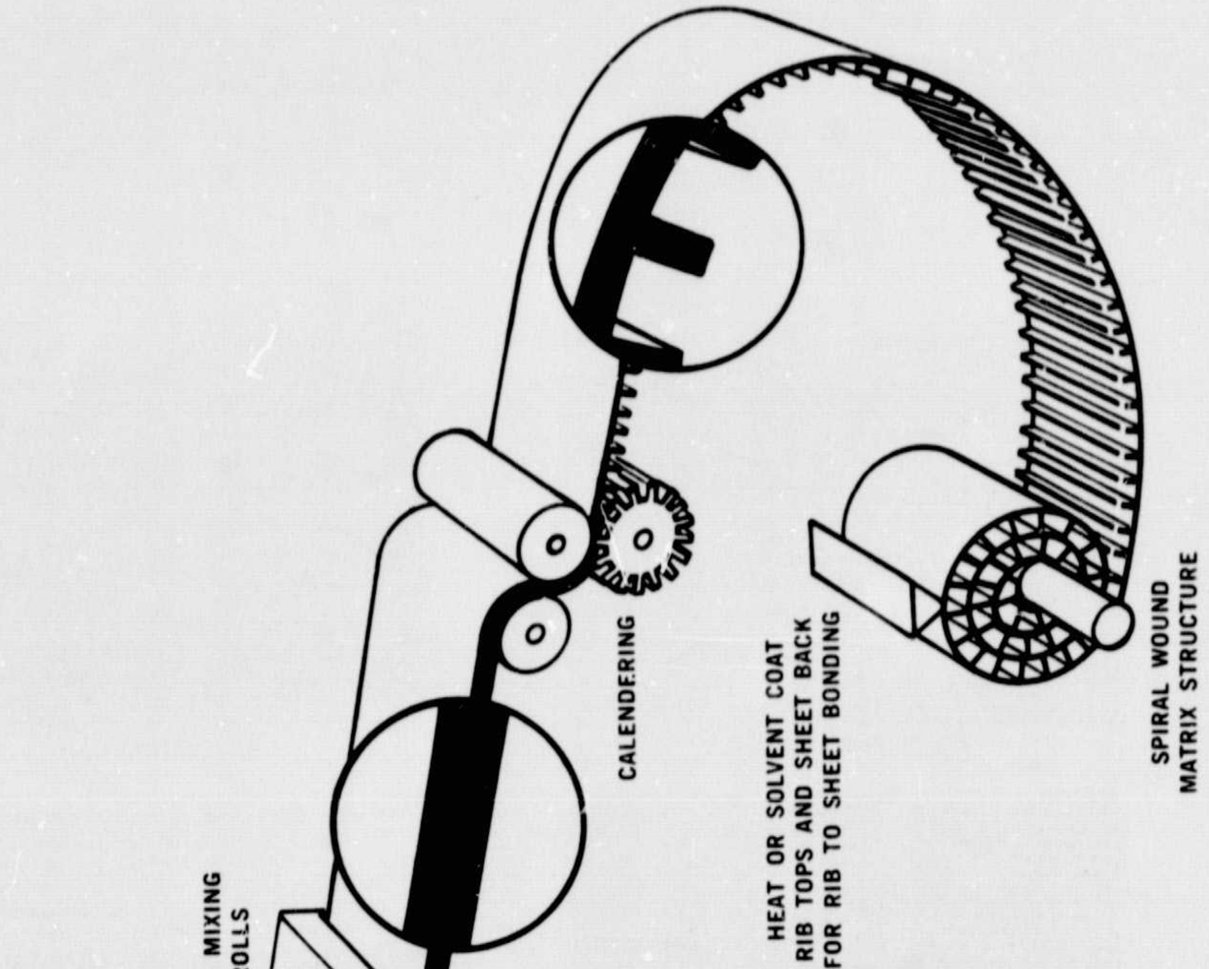


Figure 5 Typical Calendering Operation

The most difficult aspect of embossing thin wall matrices is filling the groove in the embossing roll to obtain uniform fin height with a very thin rib. A reduced rib height is desirable to alleviate this problem. This means that a moderately high aspect ratio (say 3:1 to 5:1) will be close to optimum.

The embossed tape is susceptible to buckling of the rib or back web if the rib is too high or the aspect ratio too great (Figure 4). As the ratio of rib height to thickness increases, buckling of the rib is likely to occur during the fabrication process. Deformation of the back web is likely to occur as the aspect ratio increases above about 3:1. These deformations or cell non-uniformities result in uneven flow distribution into the matrix and a loss in performance (Reference 2).

Although the embossing process for thin wall ceramic structures is not as well developed as the corrugating process discussed previously, the technology has progressed to the point where production facilities have been built to supply catalytic substrates to the automotive industry. Because of this progress, a regenerator matrix having a moderate aspect ratio passage and a 0.10 mm (0.004 in.) wall thickness appears to be feasible.

2.C EXTRUSION — In the extrusion process (Figure 6), a die can be machined to form a variety of passage geometries such as the square or isosceles triangular cell shapes which have desirable performance characteristics. In addition, the extrusion process yields the most uniform cell geometry and wall thickness. An analytical performance projection based on experimental shuttle rig data was made for an embossed and an extruded matrix with identical cell geometries. The analysis concluded that the better quality of the extruded structure would provide a 2% gain in regenerator effectiveness (Reference 2).

Both of the wrapped processes discussed previously require a good bond between the corrugation or rib and the flat sheet or back web to provide adequate strength in the finished regenerator core. Variations in bond quality can result in a number of circumferential delaminations in the matrix after sintering (Figure 4). This situation does not exist in the extruded matrix, and this could mean that this process will provide a lower manufacturing scrap rate. Obtaining thin walls and large pieces simultaneously, in addition to the uncertainty of die wear costs, are the main problem areas associated with this process.

The extruded matrix is currently in volume production as an automotive catalyst substrate. Five years ago, this process was still in the laboratory development stage. The technological progress is continuing, and the development of thin wall substrates is a high priority item since a thin wall catalyst results in both lower emissions and a smaller package. The spin-off from the catalyst development can be applied to the extrusion of a heat exchanger matrix which is similar to the substrate except for a slightly smaller hydraulic diameter flow passage.

Small matrix samples with the proper hydraulic diameter and a 0.10 mm (0.004 in.) wall thickness have been extruded. Because of the on going research and development effort, a 0.09 mm (0.0035 in.) matrix wall thickness is projected to be available shortly. Further development will be required to extrude a full size regenerator, however fabrication of a regenerator from extruded segments (Figure 6) is a viable alternative manufacturing method. It is expected that these segments would be bonded together in the green (or unfired) state, and then the entire regenerator would be fired to produce uniform physical properties as desired. This technique, which would add some additional cost to this process, has yet to be demonstrated.

To summarize, the extrusion process requires the most development (and is currently the subject of the greatest development effort). This process provides the potential of lower scrap rate, along with more uniformity and, as a result, more efficient flow passages. The major problem which must be solved is the difficulty in extruding large pieces with thin walls. Also, die wear cost for this size matrix and hydraulic diameter passage is still unknown.

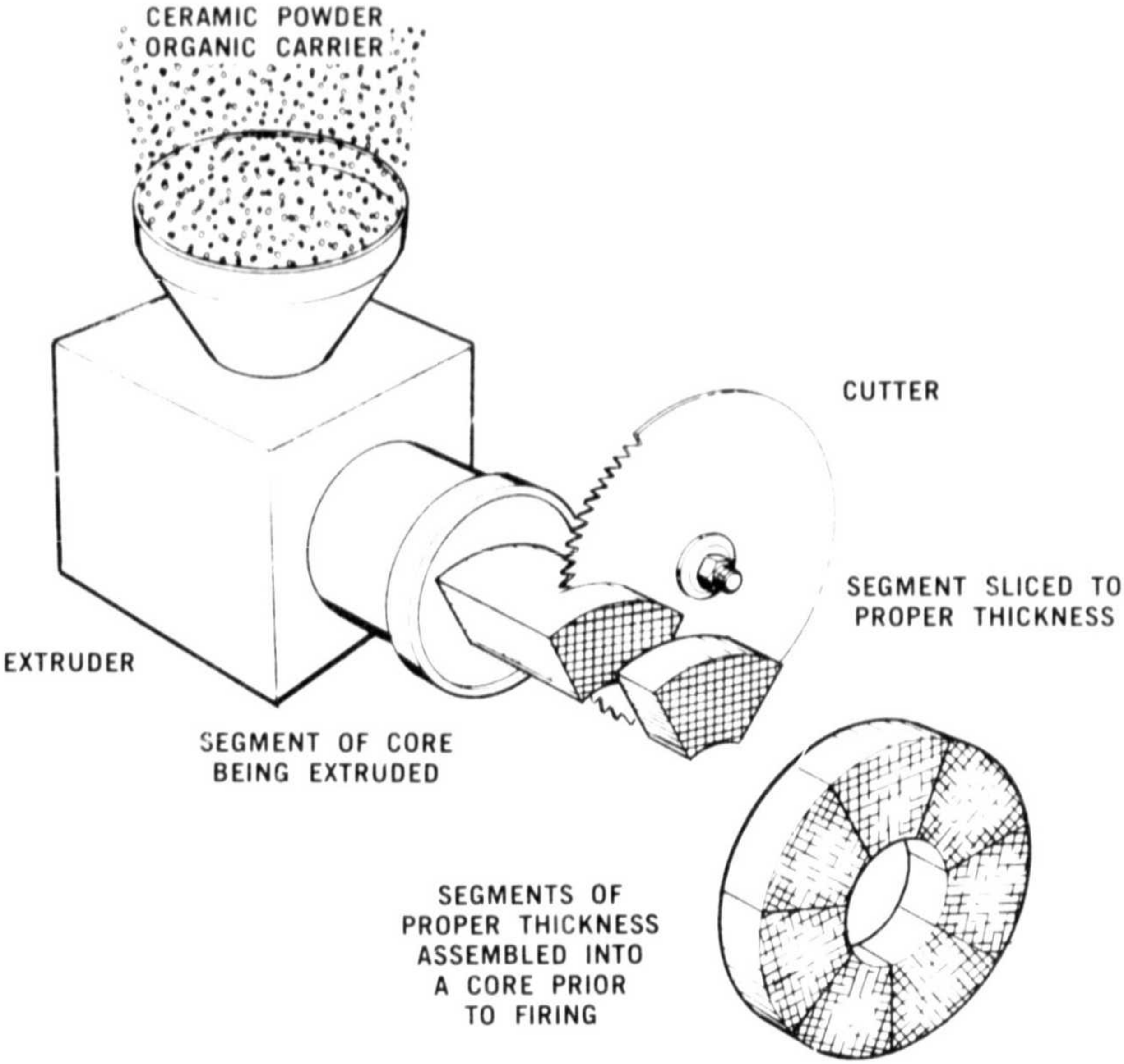


Figure 6 Typical Extrusion Operation for Fabricating a Ceramic Matrix

3.0 COST COMPARISONS

The cost of a ceramic regenerator is a function of the initial material cost and the material processing required prior to and after fabrication of the matrix. The steps in processing AS and MAS matrices will be reviewed in this section, and the costs associated with these process steps will be discussed.

3.A PROCESS STEPS — The general process steps for three MAS processes and one AS process are illustrated in Figure 7. These processes are categorized by the type of initial ceramic material that is used. Three different types could be used in the fabrication of an MAS regenerator: raw mineral, calcined mineral, and glass frit. Only the glass frit is used in fabricating an AS regenerator. In general, glass frit is easier to process and raw mineral is less expensive.

More process steps are required to fabricate a core with glass frit (Figure 9). With this approach, the extra step of melting the raw ceramic materials to create the glass frit at temperatures of 1300 to 1400°C (2375 to 2550°F) results in the increased cost. This cost may be recovered somewhat through lower firing scrap rates later on in the process. The glass frit process has an advantage in firing or bonding at lower temperatures and providing a higher matrix strength over a large portion of the firing cycle. Because of the lower kiln temperatures, firing costs and kiln maintenance are reduced somewhat when glass frit is used.

A typical MAS raw mineral preparation would include weighing and mixing of high purity talcs, clays, and aluminum oxide. In a calcining process, the batch would be heated to somewhere between 500 and 1000°C (932 and 1832°F) for a short period of time to remove all or part of the clay hydroxyl units according to the following reaction:

$$\underset{\text{(kaolin clay)}}{Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O} \longrightarrow \underset{\text{(meta kaolin)}}{Al_2O_3 \cdot 2SiO} + 2H_2O \ \text{(gas)}$$

Calcining of the talc occurs as follows:

$$\underset{\text{(talc)}}{3M_gO \cdot 4SiO_2 \cdot H_2O} \longrightarrow \underset{\text{(protoenstatite)}}{3(M_gO \cdot SiO_2)} + SiO_2 + H_2O \ \text{(gas)}$$

Some calcining is done at about 1000°C (1832°F) to convert some of the meta kaolin to mullite and cristobalite as follows:

$$\underset{\text{(meta kaolin)}}{3(Al_2O_3 \cdot 2SiO_2)} \longrightarrow \underset{\text{(mullite)}}{3Al_2O_3 \cdot 2SiO_2} + \underset{\text{(cristobalite)}}{4SiO_2}$$

The basic advantages of calcining are reducing firing shrinkage and still maintaining the high chemical reactivity during sintering that is associated with using clays and talc. Overcalcining however, must be avoided because it results in increased cost and a reduced strength in the final product because the material is more difficult to sinter.

The calcined and frit batches are then ground to provide a random distribution of particle sizes optomized for the matrix fabrication method used and the final mechanical and thermal properties desired.

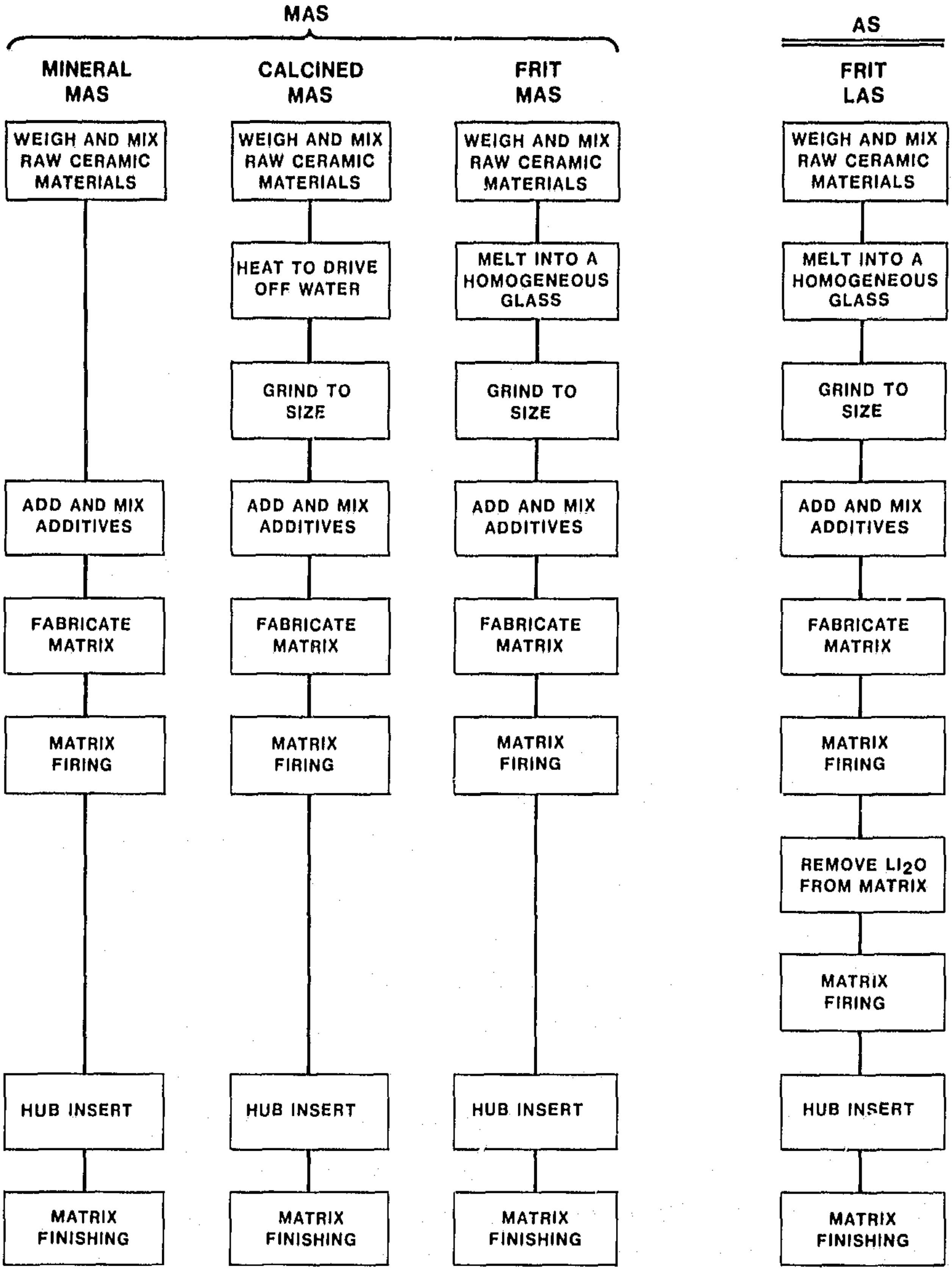


Figure 7 Regenerator Core Manufacturing Process Steps

Next, organic binders, plasticizers, release agents, etc., are added to the batch materials to provide characteristics promoting ease of matrix fabrication and green matrix strength.

The following step in the process is the fabrication of the matrix. The different fabrication processes, including corrugating, embossing, and extruding, were discussed earlier (Figures 3, 5, and 6).

The next step, matrix firing, starts by removal of the organic materials at low kiln temperatures and culminates in chemical reactions at higher temperatures which yield the desired matrix properties. At the intermediate temperatures (after binder removal and prior to particle sintering), the structure has little strength and a flexible support that can permit dimensional changes of the matrix to occur is required.

The maximum firing temperatures reached are approximately 1425°C (2600°F) and 1250°C (2300°F) for mineral and glass frit MAS respectively. For glass frit LAS, the maximum firing temperature is about 1325°C (2400°F). Even though the glass frit fires at a lower temperature than the mineral batches, the resulting lower fuel costs will not completely offset the higher frit batch cost.

Two types of kilns, tunnel or periodic, can be used to fire the green matrix. For most high volume firing applications, the tunnel kiln is desired.

For the AS matrix, additional processing is now required to convert the regenerator core from LAS material to AS material. This is accomplished by removing the lithium oxide from the finished LAS matrix by leaching in hot sulfuric acid. It is then necessary to refire the leached body, thereby promoting the formation of a high expansion phase (mullite, or $3Al_2O_3 \cdot 2SiO_2$). By closely controlling this temperature treatment, the development of a proper volume of this phase counterbalances the negatively-expanding hydrogen aluminum silicate phase and a composite bulk expansion of acceptable value can be obtained. A description of the process and final material properties are given in a recently issued patent (Reference 9).

The last step in the processing consists of finishing the regenerator core surfaces and machining the core to the required outside diameter. Although all ceramic heat exchangers are currently Blanchard ground, recent tests have shown that belt grinding has the potential for higher stock removal efficiency and lower cost.

Matrices made by corrugating or embossing ceramic tape are wound on a removable mandrel which leaves a hole in the center of the finished piece. A hub must be cemented into this hole to prevent leakage during engine operation.

3.B PROCESS COSTS — Independent ceramic heat exchanger cost studies were carried out in 1975 by five companies with experience in fabricating ceramic matrices that could be used as rotary heat exchangers (Reference 8). A 457 mm (18.0 in.) diameter ceramic air preheater for a 170 hp Stirling engine, with an annual volume of 500,000 units per year, was selected as the basis for this study. Although the size of the Stirling preheater is somewhat larger than the regenerator required for an improved gas turbine, it is believed that the same cost trends developed in this study will apply.

In the following sections of this report, it is shown that the size of the core is not influenced significantly by the choice of material or processing. This means that the gear, gear assembly, and seal costs would be the same for all materials and processes. As a consequence, the only variable that would have any major impact on the overall regenerator system cost would be the cost of the ceramic core itself.

A study of the process steps required for each type of raw material (Figure 7) indicates that a mineral MAS should be the least costly, while an AS regenerator would be the most expensive to process. The referenced cost study, which is still relevant, suggested that the choice of raw material would have the most significant effect on the finished piece cost with a 30 to 40% savings possible between AS and MAS.

The choice of fabrication process was found to have a fairly small effect on finished piece cost. The study suggested that a segmented core made by the extrusion process might result in a lower cost than a matrix wrap process by improving the yield through elimination of sheet bonding problems and the hub insert. This assumes that additional costs incurred in bonding the segments together are small and more than offset by the savings provided. Die wear and replacement costs however, are still unknown.

In summary, the cost of a ceramic regenerator is influenced most by the basic material costs. The method of matrix fabrication, whether corrugating, embossing or extruding, has relatively little effect. Because of this, a mineral MAS regenerator would be 30 - 40% less expensive to fabricate than an AS regenerator, due to the costs involved in producing a glass frit, and in leaching and refiring the AS core.

4.0 AEROTHERMODYNAMIC COMPARISONS

The parameters required for accurate heat exchanger performance prediction and sizing are the heat transfer characteristics (Colburn number, J) and the pressure drop characteristics (Fanning Friction Factor, F) of the matrix passage geometry being evaluated. As part of the NASA/FORD program (Reference 2), the heat transfer and pressure drop characteristics of more than twenty-seven matrix configurations have been evaluated. These matrix samples have been supplied by seven different sources. To obtain heat transfer and pressure drop data, a transient shuttle rig technique similar to the "sliding drawer" technique described by Howard (Reference 11 was used). The effect on efficiency of the three matrix fabrication methods previously described can be determined by evaluating the heat transfer and flow friction characteristics of the flow passage geometries resulting from each manufacturing process.

Since the corrugated sinusoidal passage with a 0.06 mm (0.0025 in.) wall thickness made from AS material has been evaluated in the shuttle rig, exact F and J data exist for this configuration (Figure 8). Heat transfer and flow friction characteristics were estimated for a thin-wall embossed rectangular configuration and an extruded isosceles triangular configuration which are expected to evolve as a result of additional development. For purposes of discussion, an embossed passage with a 0.10 mm (0.004 in.) wall thickness and a 4:1 aspect ratio was assumed (Figure 9), as was a 0.09 mm (0.0035 in.) wall thickness extruded isosceles triangular passage (Figure 10). As described in detail in the next section, the hydraulic diameter was chosen so that regenerators designed using each type of matrix would provide the same outside diameter to facilitate engine package comparisons. A tabulation of the flow passage geometries for all three matrices is presented in Table 1. The F and J data for all three matrices are shown in Figure 11. The data for the rectangular and triangular fins are estimated from shuttle rig data of matrices with similar passages and equivalent length to hydraulic diameter ratios (Reference 2).

A comparison of the matrix geometries presented in Table 1 shows that the thinner walls of the sinusoidal passage would result in more open flow area (σ) and more heat transfer surface area per unit volume (β), than the rectangular configuration, which was assigned a slightly larger hydraulic diameter (DH). These advantages are offset to some extent by the improved heat transfer characteristics (J) of the rectangular structure. Since the isosceles triangular structure exhibits much lower pressure drop characteristics (F), the hydraulic diameter can be reduced significantly. The effect is that this configuration, which has thicker walls (S), will have more heat transfer area per unit volume with lower open flow area than the sinusoidal passage.

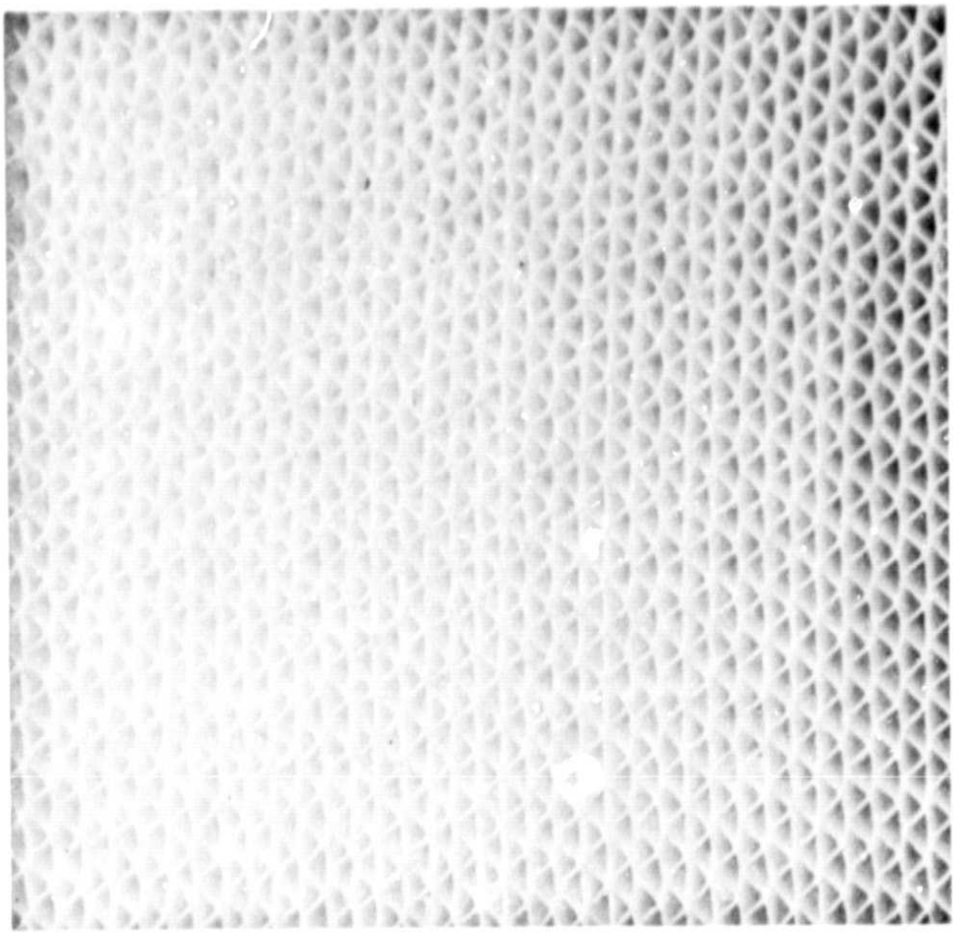


Figure 8 Corrugated Sinusoidal Fin

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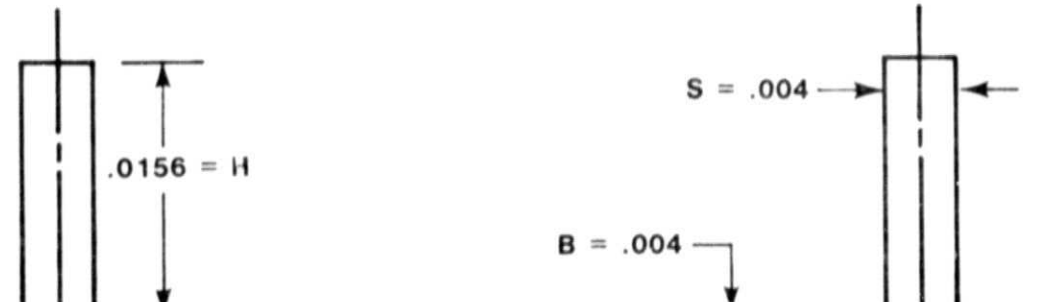
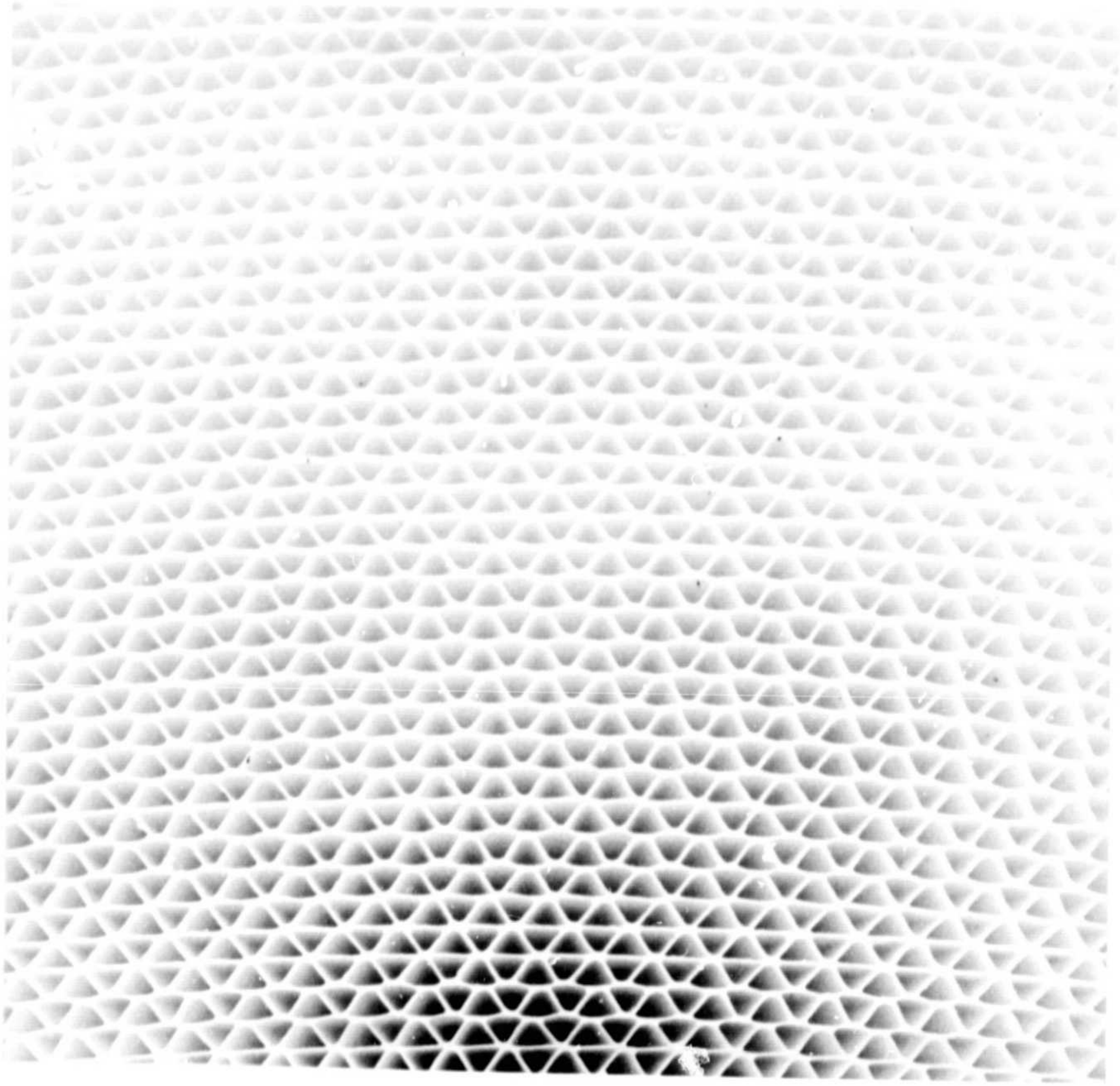


Figure 9 Embossed Rectangular Fin



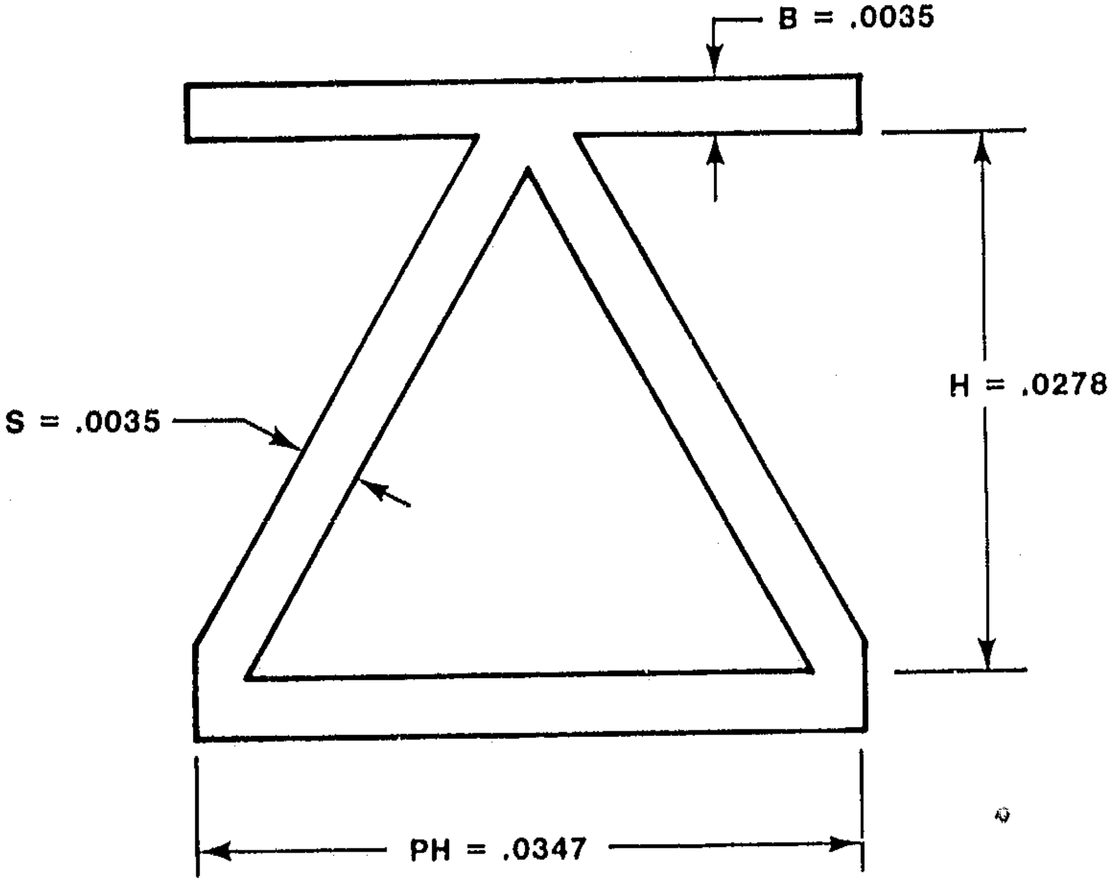
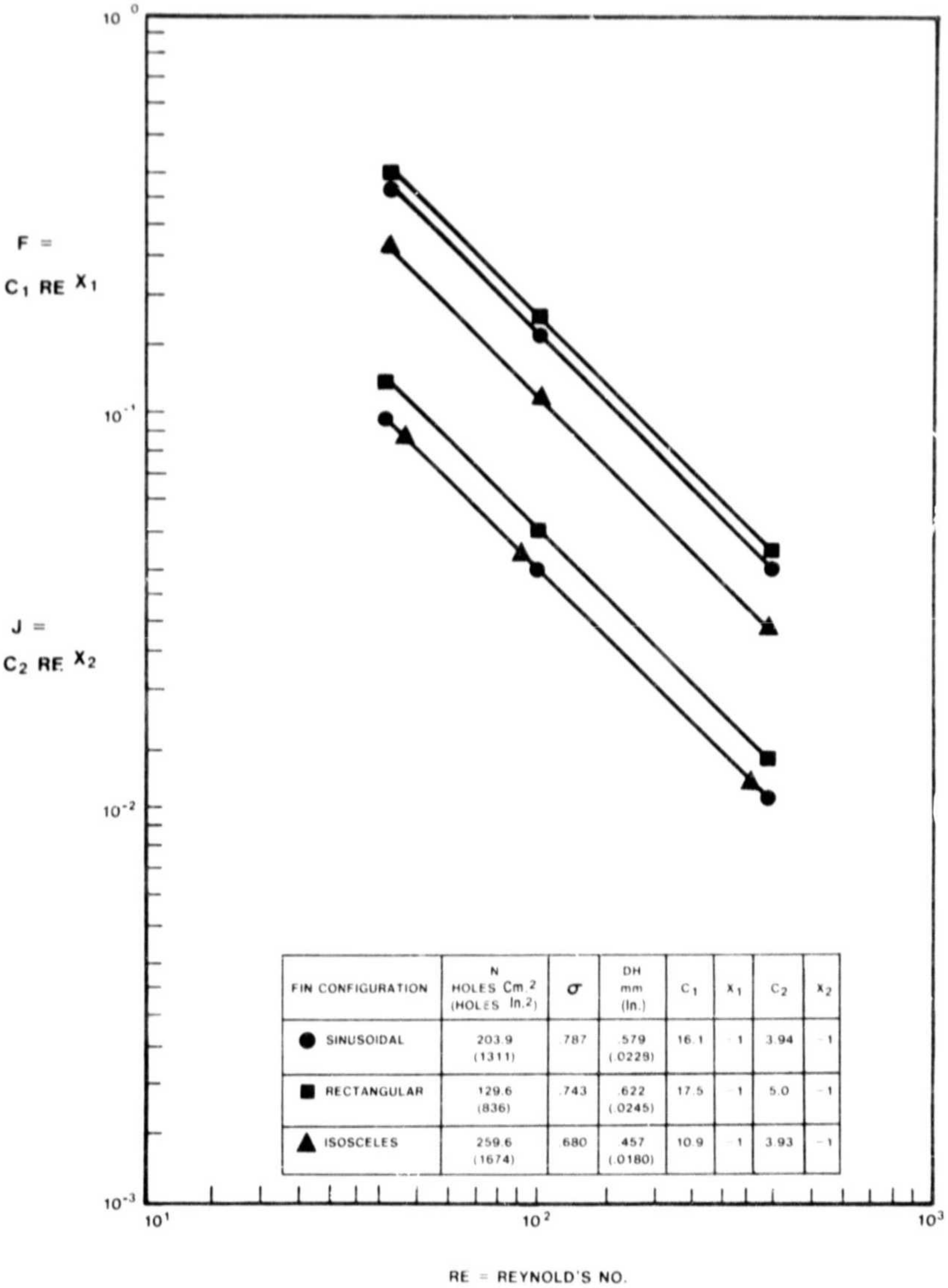


Figure 10 Extruded Triangular Fin

$$F = C_1 N_{RE}^{X_1} \qquad J = C_2 N_{RE}^{X_2}$$

COMBI-NATIONS	FIN CONFIGURATION	MANUFACTURING PROCESS	MATERIAL COMPOSITION	N $\frac{\text{HOLES}}{\text{Cm}^2}$ $\left(\frac{\text{HOLES}}{\text{In.}^2}\right)$	S mm (In.)	A.R.	σ	DH mm (In.)	β $M.^{-1}$ $(Ft.^{-1})$	C_1	X_1	C_2	X_2	J/F @ N_{RE}=10C
1	SINUSOIDAL	CORRUGATING WITH WET PAPER CARRIER	AS	203.9 (1311)	.061 (.0024)	1.98	.787	.579 (.0228)	5422 (1653)	16.1	−1	3.94	−1	.245
2	RECTANGULAR	EMBOSSING	MAS	129.6 (836)	.102 (.004)	3.90	.743	.622 (.0245)	4776 (1456)	17.5	−1	5.0	−1	.287
3	ISOSCELES	EXTRUSION	MAS	259.6 (1674)	.089 (.0035)	1.24	.680	.457 (.0180)	5958 (1814)	10.9	−1	3.93	−1	.361

Table 1 Fin Geometry Comparison



FIN CONFIGURATION	N HOLES Cm.^{2} (HOLES In.^{2})	σ	DH mm (In.)	C_1	X_1	C_2	X_2
● SINUSOIDAL	203.9 (1311)	.787	.579 (.0228)	16.1	-1	3.94	-1
■ RECTANGULAR	129.6 (836)	.743	.622 (.0245)	17.5	-1	5.0	-1
▲ ISOSCELES	259.6 (1674)	.680	.457 (.0180)	10.9	-1	3.93	-1

Figure 11 Aerothermodynamic Performance Characteristics

5.0 PERFORMANCE COMPARISONS

A better comparison of the advantages of each type of matrix can be made by designing a regenerator utilizing the fin heat transfer and pressure loss characteristics just described. In this section of the report a series of comparisons are made of regenerators that were designed with the fin data from Section 4.0 and the theory of Coppage and London (Reference 12). The two broad comparisons that were made are:

A. Regenerators were designed for identical performance, identical operating conditions and identical outside diameters, so that the only variable was the axial length. A comparison of package size could now be made for the three different matrix geometries.

B. Regenerators were designed for equal outside diameter and length and operated under identical flow conditions. A direct comparison of performance could be made for the three different matrix geometries.

The engine conditions selected for this comparison are listed in Table 2. These conditions are typical of an improved 100 hp automotive gas turbine. The 60% gas generator speed condition with a regenerator inlet temperature of 1009°C (1848°F) simulates the average power load and fuel flow experienced on the Metro-Highway route in a 2500 to 3000 pound vehicle.

5.A REGENERATOR SIZE FOR EQUAL PERFORMANCE – A regenerator was designed using each of the flow geometries described in Section 4.0 for the 60% gas generator speed condition listed in Table 2. The performance of each regenerator was maintained the same, with an effectiveness of 96% and a total pressure loss of 2.5% of total pressure. As mentioned previously, the hydraulic diameters of the matrix passages were adjusted so that the regenerator core outside diameters were approximately equal. A comparison of the geometries is shown in Table 3.

N_{GG} %	FLOW CONDITIONS	REGENERATOR SIDE	
		HIGH PRESSURE	LOW PRESSURE
60	FLUID MASS FLOW RATE, Kg/Sec. (Lb./Sec.)	.117 (.257)	.118 (.260)
	INLET TEMPERATURE, °C. (°F.)	97 (207)	1009 (1848)
	INLET PRESSURE, KPa (psia)	182.6 (26.49)	103.6 (15.02)
100	FLUID MASS FLOW RATE, Kg/Sec. (Lb./Sec.)	.368 (.812)	.380 (.838)
	INLET TEMPERATURE, °C. (°F.)	257 (495)	807 (1485)
	INLET PRESSURE, KPa (psia)	511 (74.11)	109.5 (15.89)
50	FLUID MASS FLOW RATE, Kg/Sec. (Lb./Sec.)	.101 (.222)	.103 (.228)
	INLET TEMPERATURE, °C. (°F.)	86 (187)	1006 (1843)
	INLET PRESSURE, KPa (psia)	167.2 (24.26)	103.3 (14.98)

Table 2 Engine Performance Conditions Selected for Regenerator Comparison

DESIGN REQUIREMENTS:

$\epsilon = 96.0\%$

$(\Delta P/P)_T = 2.6\%$

$N_{GG} = 60\%$

$F = C_1 N_{RE}{}^{X_1}$

$J = C_2 N_{RE}{}^{X_2}$

COMBI-NATIONS	FIN CONFIGURATION	MANUFACTURING PROCESS	MATERIAL COMPOSITION	N HOLES/Cm^2 (HOLES/In.^{2})	S mm (In.)	A.R.	σ	DH mm (In.)	β M^{-1} (Ft.$^{-1}$)	C_1	X_1	C_2	X_2	D_0 Cm (In.)	D_1 Cm (In.)	L Cm (In.)	VOLUME Cm^3 (In.^{3})
1	SINUSOIDAL	CORRUGATING	AS	203.9 (1311)	.061 (.0024)	1.98	.787	.579 (.0228)	5422 (1653)	16.1	−1	3.94	−1	34.3 (13.5)	5.1 (2.0)	6.5 (2.57)	5883 (359)
2	RECTANGULAR	EMBOSSING	MAS	129.6 (836)	.102 (.004)	3.90	.743	.622 (.0245)	4776 (1456)	17.5	−1	5.0	−1	34.0 (13.4)	5.1 (2.0)	6.5 (2.54)	5703 (348)
3	ISOSCELES	EXTRUSION	MAS	259.5 (1674)	.089 (.0035)	1.24	.680	.457 (.0180)	5950 (1814)	10.9	−1	3.93	−1	33.8 13.3	5.1 2.0	5.0 1.98	4359 (266)

Table 3 Regenerator Geometry Comparison for Equal Performance

The lower wall thickness of the wrapped, sinusoidal matrix overcame the inherent inefficiencies associated with the sinusoidal passage, and this configuration resulted in a regenerator core that is essentially the same size as the core that incorporates the more efficient embossed rectangular passage. The lower hydraulic diameter of the extruded isosceles triangular configuration necessitates a thinner core to attain an equivalent outside diameter. It should be noted that all three matrices had approximately the same outside diameter and the poorest configuration was 15 mm (0.59 in.) thicker than the best. Although some inaccuracy exists in measuring or estimating the F and J data used in the analysis, it is believed that the trends shown here are realistic. It is concluded therefore, that the extruded isosceles triangular matrix will result in a reduction in regenerator package size compared to the other geometries, since it is at least 14 mm (0.56 in.) thinner than the other two.

To verify this conclusion for other regenerator systems, the study was repeated by designing three regenerator systems for improved fuel economy. The objective here was to provide an effectiveness of 97% and a total pressure loss of 2% of total pressure. The outside diameters were again held approximately equal and the length of each core was varied to provide the required performance. The results are presented in Table 4 and show that both the diameter and length must be increased for each matrix to obtain the better performance. The same trend reappears with the triangular passage resulting in the smallest regenerator and the sinusoidal passage providing the largest, confirming the relative efficiencies of the three systems. The difference in length is again significant, since the triangular core is 14 mm (0.54 in.) thinner than the sinusoidal and 13 mm (0.51 in.) thinner than the rectangular.

5.B REGENERATOR PERFORMANCE FOR EQUAL SIZE — In the course of an engine development program, one type of regenerator core may frequently be substituted for another. The results of such a substitution could be obtained from Table 5 where the performance for the three regenerators are compared when all three have the same outside diameters and thicknesses. Again, the 60% gas generator speed operating condition from Table 2 was used for this comparison. The performance of the embossed rectangular structure is only slightly better, about 0.2% gain in effectiveness, than that of the corrugated sinusoidal configuration. A gain in effectiveness, of about 1.1% which is partially offset by the higher pressure drop, is evident with the extruded isosceles triangular configuration. In order to evaluate the effect of regenerator performance on engine fuel economy, an engine cycle analysis computer program was used to evaluate each regenerator for the conditions specified in Table 2. The results of this analysis indicate that the embossed and extruded configurations provide a gain in fuel economy of 0.9% and 3.4% respectively compared to the sinusoidal structure at the 60% gas generator speed condition (Table 5). Although the gain in economy is within the accuracy of the calculation, it is believed that the trend is valid and that the extruded isosceles triangular configuration appears to have a 2-1/2% to 3-1/2% performance advantage over the others.

5.C OTHER PERFORMANCE CONSIDERATIONS — Other factors affect the performance characteristics of regenerators made from the various combinations of materials and fabrication processes. Five such factors will be discussed in this section:

1. Carry over leakage
2. Internal leakage
3. Variations in performance throughout the engine operating range
4. Seal leakage
5. Assembly of the gear to the regenerator

DESIGN REQUIREMENTS:

$\epsilon = 97\%$

$(\Delta P/P)_T = 2.0\%$

$N_{GG} = 60\%$

$F = C_1 N_{RE}^{X_1}$

$J = C_2 N_{RE}^{X_2}$

COMBI-NATIONS	FIN CONFIGURATION	MANUFACTURING PROCESS	MATERIAL COMPOSITION	N $\frac{HOLES}{Cm^2}$ $\left(\frac{HOLES}{In.^2}\right)$	S mm (In.)	A.R.	σ	DH mm (In.)	β M^{-1} $(Ft.^{-1})$	C_1	X_1	C_2	X_2	D_0 Cm (In.)	D_1 Cm (In.)	L Cm (In.)	VOLUME Cm^3 $(In.^3)$
1	SINUSOIDAL	CORRUGATING	AS	203.9 (1311)	.061 (.0024)	1.98	.787	.579 (.0228)	5422 (1653)	16.1	−1	3.94	−1	38.1 (15.0)	5.1 (2.0)	6.7 (2.65)	7522 (459)
2	RECTANGULAR	EMBOSSING	MAS	129.6 (836)	.102 (.004)	3.90	.743	.622 (.0245)	4776 (1456)	17.5	−1	5.0	−1	37.8 (14.9)	5.1 (2.0)	6.7 (2.62)	7325 (447)
3	ISOSCELES	EXTRUSION	MAS	259.5 (1674)	.089 (.0035)	1.24	.680	.457 (.0180)	5950 (1814)	10.9	−1	3.93	−1	38.1 (15.0)	5.1 (2.0)	5.4 (2.11)	6014 (367)

Table 4 Regenerator Geometry Comparison for Equal Performance

N_{GG} = 60%
D_O = 34.3 Cm. (13.5 in.)
D_I = 5.1 Cm. (2.0 in.)
L = 6.5 Cm. (2.57 in.)
RS = 15 RPM

$F = C_1 N_{RE}{}^{X_1}$

$J = C_2 N_{RE}{}^{X_2}$

COMBI-NATIONS	FIN CONFIGURATION	MANUFACTURING PROCESS	MATERIAL COMPOSITION	N $\frac{\text{HOLES}}{\text{Cm}^2}$ $\left(\frac{\text{HOLES}}{\text{In.}^2}\right)$	S mm (In.)	A.R.	σ	DH mm (In.)	β M^{-1} $(Ft.^{-1})$	C_1	X_1	C_2	X_2	ϵ %	$(\Delta P/P)_T$ %	GAIN IN ENGINE SFC %
1	SINUSOIDAL	CORRUGATING	AS	203.9 (1311)	.061 (.0024)	1.98	.787	.579 (.0228)	5422 (1653)	16.1	−1	3.94	−1	95.9	2.63	0
2	RECTANGULAR	EMBOSSING	MAS	129.6 (836)	.102 (.004)	3.90	.743	.622 (.0245)	4776 (1456)	17.5	−1	5.0	−1	96.1	2.62	0.9
3	ISOSCELES	EXTRUSION	MAS	259.5 (1674)	.089 (.0035)	1.24	.680	.457 (.0180)	5950 (1814)	10.9	−1	3.93	−1	97.0	3.29	3.4

Table 5 Regenerator Performance Comparison for Equal Size

Carry over leakage, or the amount of high pressure air that is trapped in the core as it rotates under the crossarm seal, represents a performance loss. This leakage is a function of the crossarm seal width, core rotational speed, core volume, and open area. If the first two factors are held constant, the carry over leakage is only a function of volume and open area. These values, as well as the percent leakage, are listed for all three configurations in Table 6, based on the volumes required for equal performance from Table 4. The difference in carry over leakage among all three configurations is very small, amounting to less than 0.15% of engine air flow. Therefore, this factor can safely be ignored.

Wall porosity in the ceramic matrix can result in an internal leakage of the high pressure air into the low pressure region and an attendant loss in engine performance. A method of statically measuring this leakage is described in the Material Specification included in the Appendix of Reference 13. The maximum permitted value of this leakage is also included in this specification. Internal leakage tests have been conducted on thin-wall AS cores made with the wrapped, corrugated sheet process. These tests have shown that the internal leakage of this material - process combination is acceptable. As noted in Section 1.0, MAS material tests suggest that this material may have greater strength and less porosity than the AS material. In addition, the thicker walls used in the embossed and extruded matrices will tend to inhibit internal leakage. For these reasons, it is believed that internal leakage will also be within the acceptable range for the MAS cores.

So far, the performance of the three configurations has been compared only at 60% gasifier speed. The regenerators defined in Table 4 were evaluated throughout the engine operating range and the results are presented in Figure 12. The regenerator flow conditions at idle and full power are included in Table 2. It can be seen that all three configurations provide virtually identical performance for low speed engine operating points. The performance effects of the three geometries become evident at higher gas generator speed conditions, with the extruded core developing the best performance.

FIN CONFIGURATION	σ	VOLUME* Cm.3 (In.3)	CARRY-OVER LEAKAGE Kg/Sec. (Lb/Sec.)	% ENGINE AIR FLOW
1. CORRUGATED SINUSOIDAL	.787	7522 (459)	.00050 (.00110)	.43
2. EMBOSSED RECTANGULAR	.743	7325 (447)	.00046 (.00102)	.40
3. EXTRUDED ISOSCELES	.680	6014 (367)	.00035 (.00076)	.30

* VOLUME REQUIRED FOR EQUIVALENT PERFORMANCE FROM TABLE 4 WITH RS = 15 RPM

Table 6 Regenerator Leakage

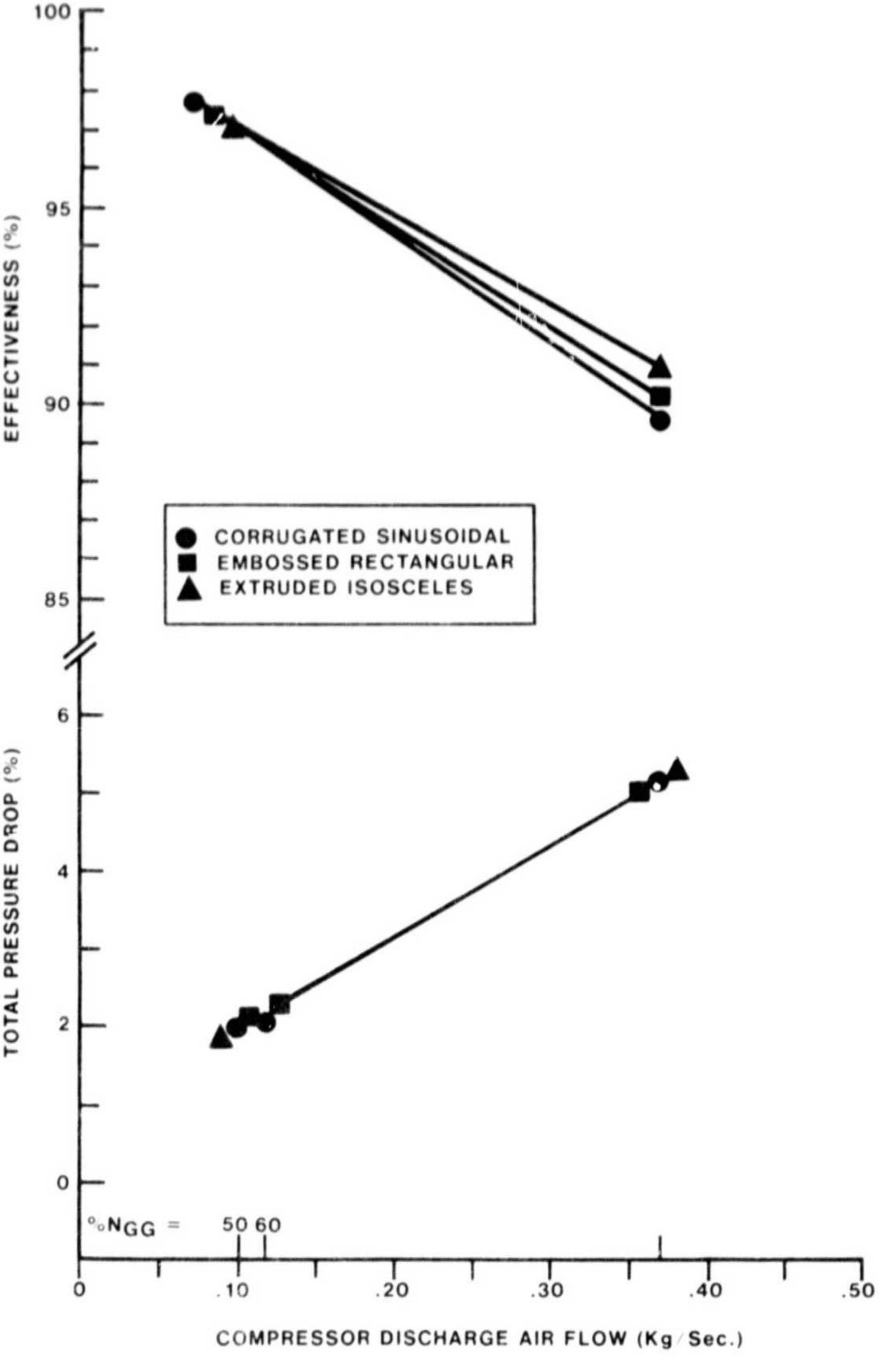


Figure 12 Regenerator Performance vs. Engine Speed

Regenerator rubbing shoe seal leakage is influenced by seal shoe and regenerator matrix surface wear. The thin-wall sinusoidal AS regenerators which have operated in the Ford 707 engine at temperatures up to 1000°C (1832°F) have shown no indication of excessive seal or core wear (Reference 2). Full size MAS regenerators with embossed rectangular passages, and MAS matrix core inserts with extruded isosceles triangular passages have also been operated in the Ford 707 turbine with no adverse effects. Even though these MAS matrices incorporated thicker walls than those considered here, it is believed that neither seal shoe nor matrix wear will constitute a problem with these types of cores. Lack of experimental test data precludes any comment being made about operation at temperatures greater than 1000°C (1832°F).

The Ford regenerator support system is a three-point rim support design using an elastomer bonded ring gear (Figure 13). In this system the ring gear is bonded to the core at an elevated temperature. This is done for a number of reasons: the elevated temperature bonding promotes elastomer cross-linking and minimizes the effects of heat aging during operation. It also may be used to provide a radial compressive preload in the core at room temperature which is desirable to counteract the tendency of the differential thermal expansion between the gear and the core to impose a radial tensile load on the core during start-up transient operation. A radial compressive load also tends to counteract operating tangential tensile stresses in the rim of higher expansion regenerators such as MAS.

Particular problems were encountered in bonding ring gears to 0.06 mm (0.0025 in.) wall thickness sinusoidal passage AS regenerators in that the compressive load applied during assembly tended to damage the rim, resulting in either immediate failure of the core in the assembly fixture, or eventual ring gear separation during engine operation. Recently, a compliant elastomer configuration which retains the advantages of high temperature bonding to avoid heat aging difficulties, and essentially divorces the ring gear from the core in order to overcome the differential thermal expansion problem has begun engine evaluation. The compliant configuration consists of thin elastomer pads bonded alternately to the gear and the core, and connected by thin elastomer beams such that nowhere around the rim is the gear bonded directly to the core (Figure 14). Continued engine evaluation of this or similar schemes will establish whether a solution to this problem has been determined.

Similar incidents of ring gear separation have not occurred with MAS regenerators due to the fact that the MAS regenerator cores engine tested to date have possessed a thicker wall than the thin-wall AS cores and, consequently, the radial compressive strength has been greater. As noted in Section 1.0, the basic strength of MAS may be equal to or greater than that of AS. This suggests that no greater difficulty should be experienced in bonding a ring gear to MAS cores than is currently encountered with AS cores. Since an elastomer design has evolved for the thin-wall AS core which shows promise of achieving acceptable durability, this problem should not be an issue in the selection of future regenerator configurations.

In summary, the extruded isosceles triangular configuration regenerator provides better performance than either the sinusoidal or rectangular configurations. In particular, a 2-1/2 to 3-1/2% engine fuel economy advantage is provided at the 60% gas generator speed condition typical of the automotive application. In terms of leakage and ease of assembly, all of the configurations appear to be equally acceptable.

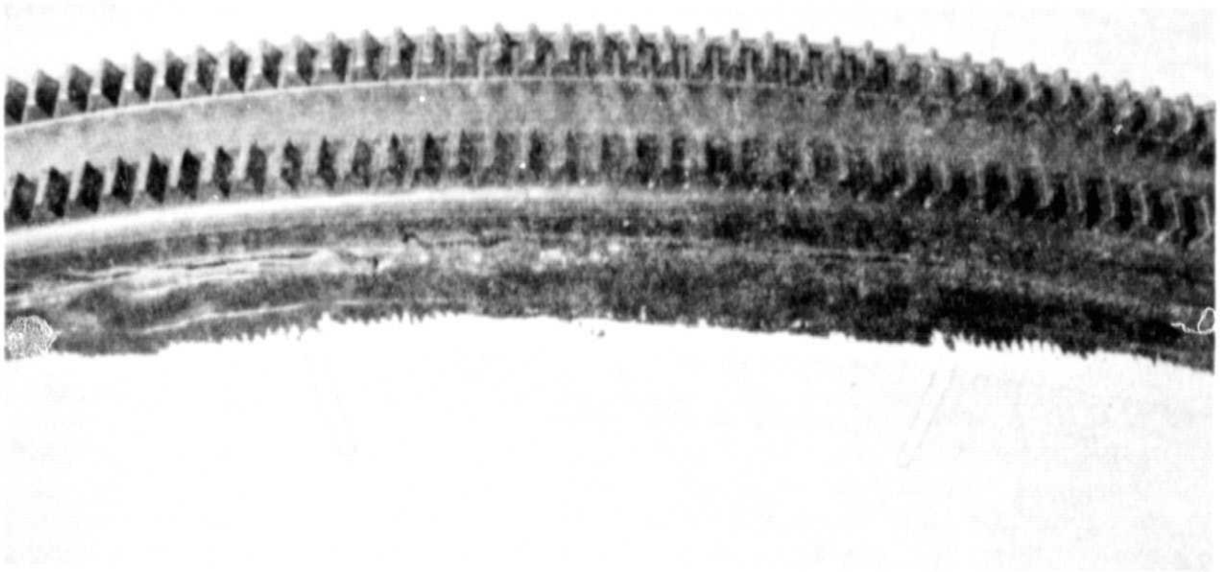


Figure 13 Ford 707 Turbine Engine Core with Elastomerically Bonded Ring Gear

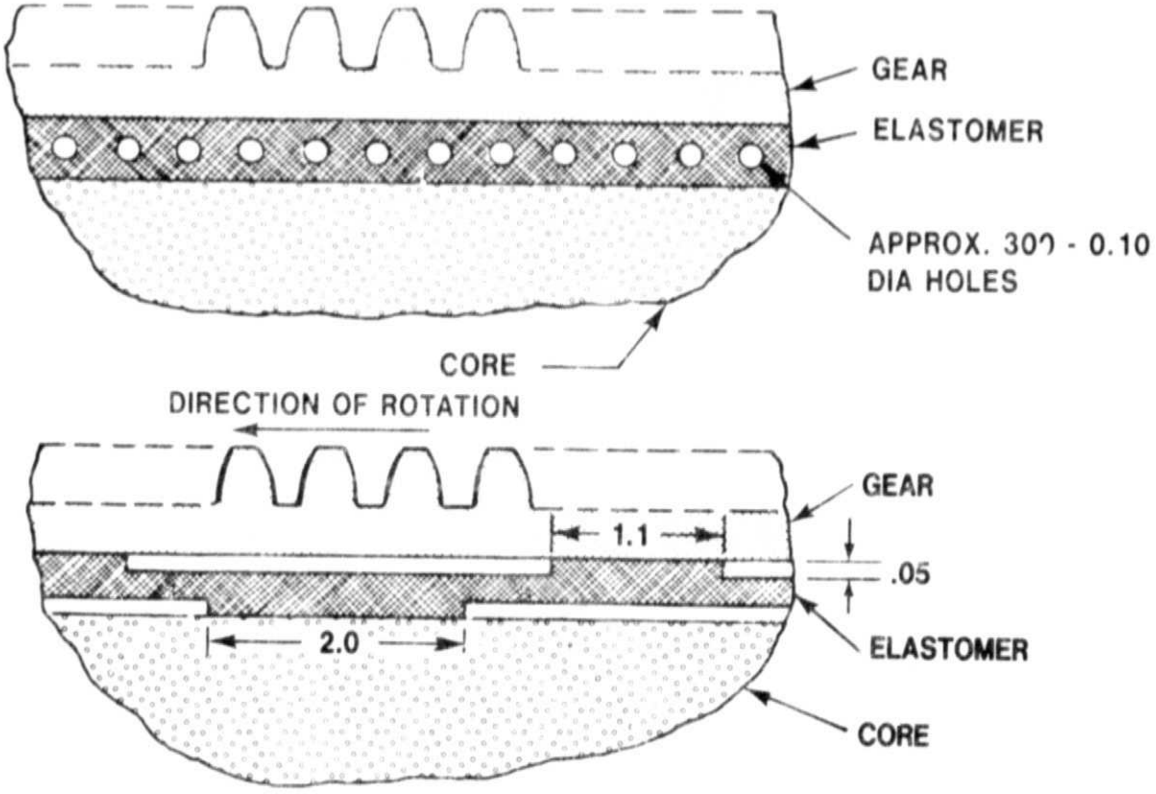
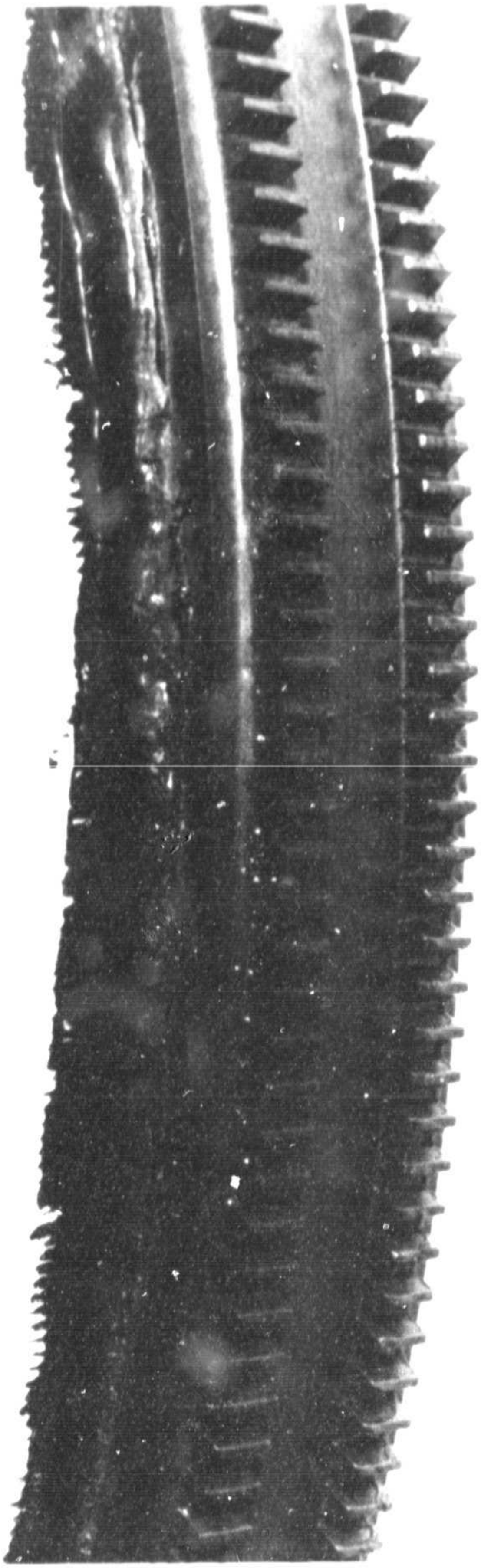


Figure 14 Compliant Elastomer Scheme



CONCLUSIONS

COST — Of the three manufacturing processes reviewed (corrugating, embossing, and extruding), none shows a distinct cost advantage over the others and all have the potential for high volume fabrication of regenerators. The process which may have the greatest potential for lower cost fabrication is the extrusion, although this may be dependent on die wear costs (which are currently unknown), and the costs involved in assembling extruded segments to form a complete regenerator if a one-piece fabrication is not possible.

In terms of materials, a 30-40% cost savings over AS can be realized if a MAS material (and in particular, a raw mineral MAS) is used for heat exchanger fabrication rather than an AS material.

DURABILITY — Both AS and MAS have demonstrated the capability for satisfactory operation at 800°C (1472°F), and it is probable that they are both capable of satisfactory operation at 1000°C (1832°F).

The potential for either AS or MAS regenerators to operate for long periods of time at temperatures above 1000°C (1832°F) is uncertain for the present generation of these materials. Present AS materials are thermally unstable at 1100°C (2012°F), and the high thermal expansion characteristics of MAS materials result in prohibitively high thermal stresses. Both the instability and stress could cause core failures. It is possible that the high temperature operating potential of both materials can be improved with additional development.

PERFORMANCE — A performance advantage associated with an extruded matrix is that this manufacturing process yields the most uniform cell geometry. Consequently, extruded matrices are not subject to efficiency losses as a result of fabrication induced flaws to the same extent as matrices produced by a wrapping process.

It was estimated that in the future, embossed rectangular regenerators can be made with a 0.10 mm (0.004 in.) wall thickness and an extruded triangular matrix can be fabricated with a 0.09 mm (0.0035 in.) wall thickness. The corrugated sinusoidal matrix is currently being fabricated with a 0.06 mm (0.0025 in.) wall thickness. An evaluation of each of these passage geometry configurations indicates that the extruded isosceles triangle shape provides the best combination of heat transfer and flow friction characteristics, followed by the embossed rectangular configuration, and then the corrugated sinusoidal passage.

An analysis of regenerators incorporating these matrix configurations indicates that for equivalent core outside diameter and performance at a specified engine operating condition, the extruded isosceles triangle passage would provide the minimum thickness core. When the same structures are compared at a fixed package size (equal thickness and outside diameter), the extruded isosceles triangle matrix would have a 2-1/2% to 3-1/2% advantage in fuel economy, over the rectangular and sinusoidal matrices, respectively.

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DEFINITION OF SYMBOLS

B = Plate thickness, mm (in.)

C_1 = Laminar flow constant for fanning friction factor

C_2 = Laminar flow constant for Colburn number

DH = Hydraulic diameter, mm (in.)

D_I = Regenerator inner diameter, cm (in.)

D_o = Regenerator outer diameter, cm (in.)

H = Fin height, mm (in.)

L = Regenerator thickness, cm (in.)

N = Matrix cell density, openings/ cm^2 (openings/ in.^2)

P = Inlet pressure, kpa (psia)

PH = Fin pitch, mm (in.)

RS = Regenerator speed, rpm

S = Fin thickness, mm (in.)

X_1 = Reynold's number exponent for fanning friction factor

X_2 = Reynold's number exponent for Colburn number

β = Heat transfer surface area per unit volume, m^{-1} (ft.^{-1})

E = Heat exchanger effectiveness

σ = Ratio of flow cross section area to matrix frontal area

NONDIMENSIONAL GROUPINGS

A.R. = Matrix fin aspect ratio, PH/H

F = Fanning friction factor, $C_1 N_{re}^{X_1}$

J = Colburn number, $C_2 N_{re}^{X_2}$

N_{re} = Reynolds number