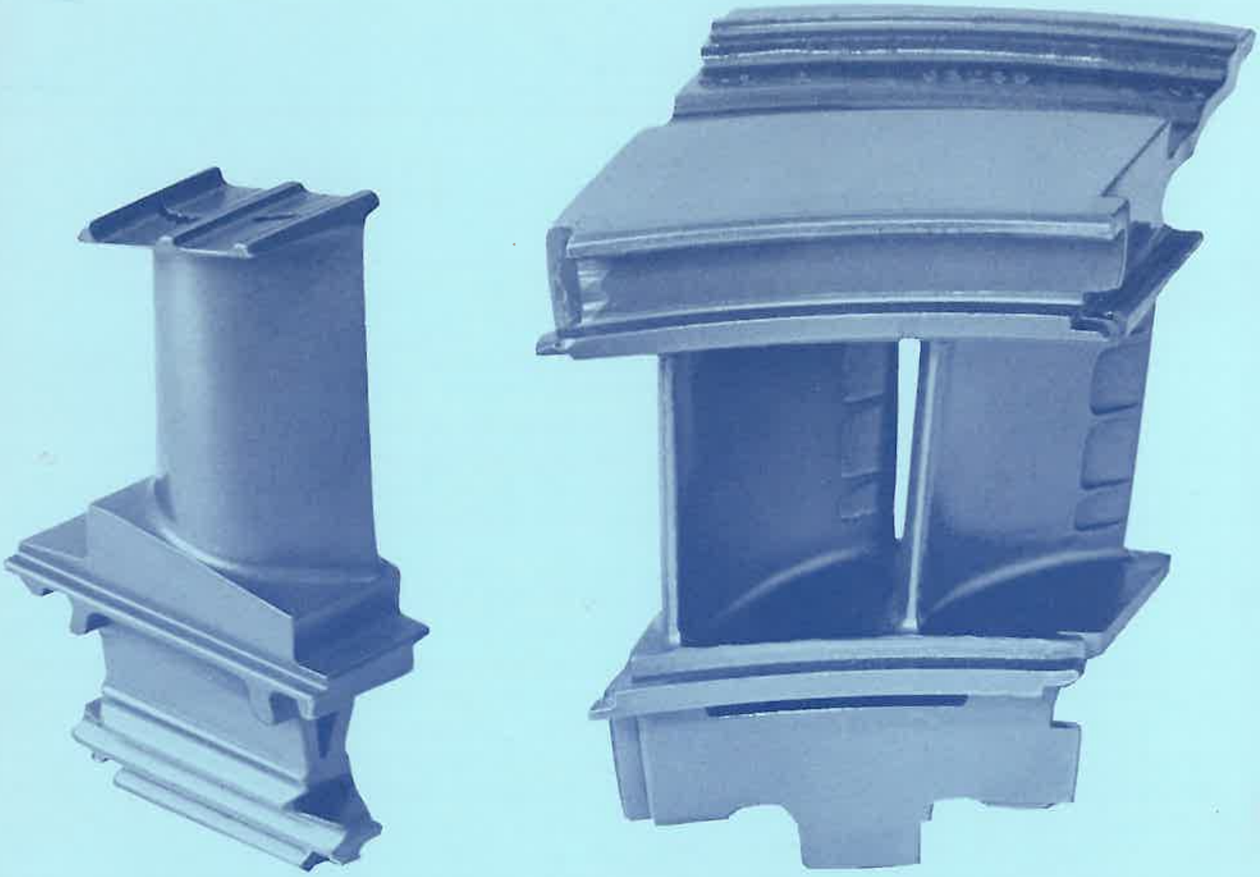

Air Cooled first stage Allison 501-K
Gas Turbine Vanes and Blades

The Factor That Makes The Difference In Gas Turbine Engines

Preface

The single, most critical factor in gas turbine operation is firing temperature. The higher the firing temperature, the greater the power output with a corresponding lower specific fuel consumption. However, firing temperature is limited by the ability of the materials to withstand heat.

In the Allison 501-K air cooling process, the turbine utilizes a small percentage of compressor discharge air and directs it through the hollow first stage blades and vanes. It has therefore been possible to increase the firing temperature in the engine to achieve higher horsepower without an increase in metal temperature. At the same time, the additional performance obtained is accompanied by a reduction in specific fuel consumption.

Common turbine fuels and the atmosphere contain certain compounds of elements such as sulfur and vanadium that have a corrosive effect on blades and vanes, reducing their service life. The 501-K incorporates metallurigcal processes and surface coatings designed to resist these corrosive elements. This technology, in combination with the air cooling technique, has substantially increased the service life of the turbine blades. The significance of the air cooling concept becomes clearer with these facts in mind.

This report is published by Detroit Diesel Allison as information to prospective customers. It is designed to inform the reader of the history and technology of the Allison 501-K air cooled gas turbine engine. The 501-K is a leading power source for industrial and marine applications and the air cooling technique which it incorporates was pioneered by Detroit Diesel Allison and has become today's standard of the turbine industry.

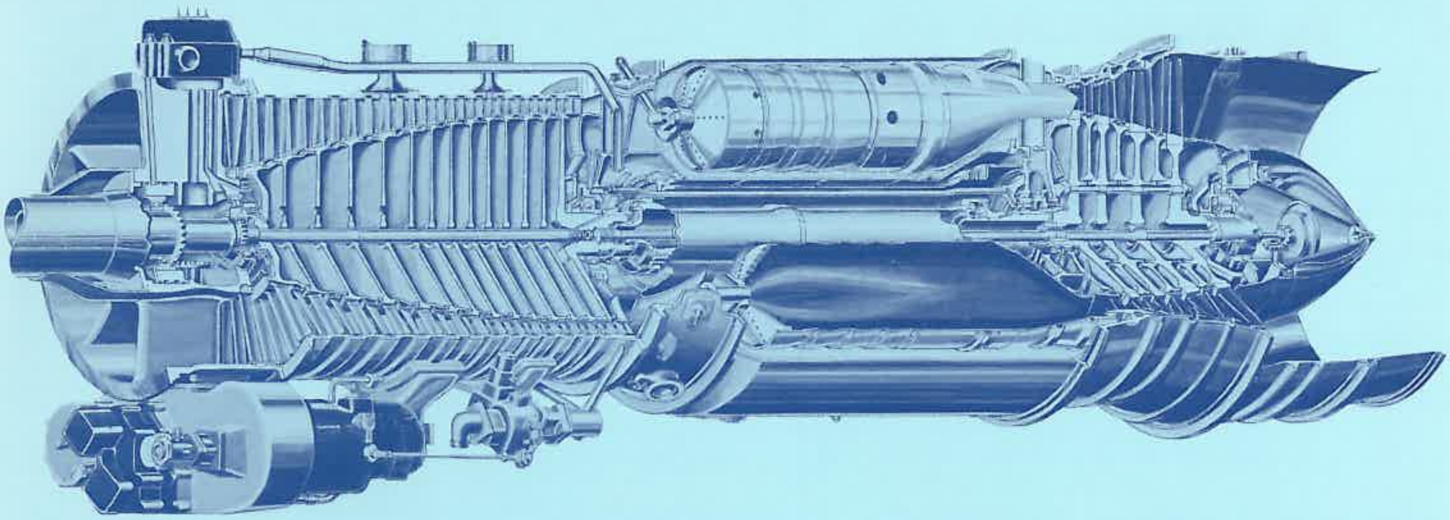

Figure 1. The Allison 501-K Series III air cooled gas turbine engine.

An Introduction to Air Cooled First Stage Blades and Vanes

The Allison 501-K industrial gas turbine engine, shown in Figure 1, represents over 20 years of production and continued development. The engine has established a measurable record of reliability and performance by accumulating in excess of 60,000,000 hours of operation throughout the world in aircraft and industrial applications. Production has exceeded 11,000 engines, with an ever-increasing demand for shaft propulsion power.

The "aircraft derivative" 501-K turbine engine has made a significant contribution in fulfilling the expanding requirements for a lightweight, high horsepower, low fuel rate, maintainable prime mover with an impressive time between overhauls. The high production volume, advanced design, metallurgical developments, turbine coating techniques, modular construction and other features introduced by Detroit Diesel Allison make the engine suitable for the turbine applications where low cost and high power at a low fuel rate is essential.

The millions of dollars and thousands of test hours expended to develop a practical turbine air cooling system for aircraft engines, both military and commercial, are now reflecting benefits in the areas of performance, fuel economy, and component durability for industrial use. The 501-K has now progressed through three generations of development, from the initial industrial rating of 2400 horsepower (1800 KW) to approximately 5000 horsepower (3700 KW). The innovation, refinement, and volume production of air cooled blades and vanes permit firing the engine at increased turbine inlet temperatures, thereby producing more power at a reduction in the specific fuel rate, while at the same time increasing the service life of the parts. This technique was pioneered at Detroit Diesel Allison and incorporated into production engines well in advance of other manufacturers.

The actual measured metal temperature of air cooled blades and vanes is considerably less than that of solid conventional blades or vanes even when operating at higher firing temperatures. Time between overhauls in excess of 30,000 hours has been recorded with the air cooled system.

The design features of 501-K air cooled blades and vanes, fabrication techniques, material selection standards, coating procedures for sulfidation protection, and product improvement programs are described in further detail on the following pages to substantiate the performance and reliability of the Allison 501-K gas turbine engine.

Design Features

As shown in Figure 2, engine air flow of approximately 1% — is metered into the turbine blade hollow stalk, where it flows through the internal fins to exit at the tip. This cooling reduces the blade average metal temperature by approximately 200 degrees F (93°C) at full power.

The incorporation of the hollow stalk section of the blade reduces the turbine wheel diameter and moves the wheel out of the hot combustion gas path, thereby lowering the rim temperature by several hundred degrees which increases the wheel service life.

The first three stages of the four stage turbine have shrouded blades to reduce gas leakage past the blade tips.

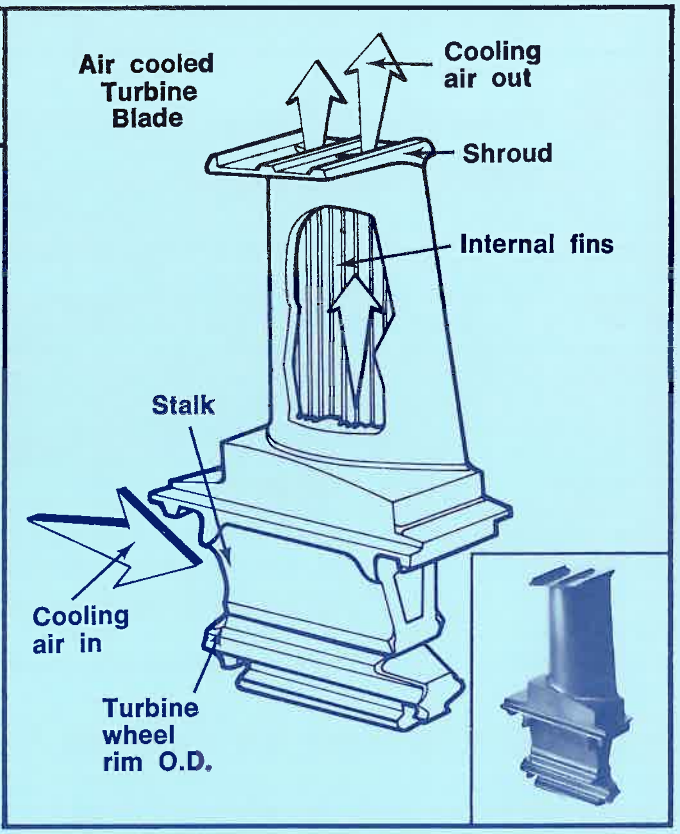

Figure 2. Air flow in air cooled turbine blade.

As shown in Figure 3, the turbine vane air flow is 2½% of the engine air flow and is distributed through six small jets, impinging against the inside surface of the leading edge of each air foil. The cooling air then flows rearward past the internal fins to exit near the air foil trailing edge.

An additional internal air jet discharges rearward to provide cooling for the inside surface of the outer portion of the air foil trailing edge. The cooling reduces the average vane metal temperature by approximately 350 degrees F (176°C) below the surrounding gas temperature, and again substantially increases the vane service life.

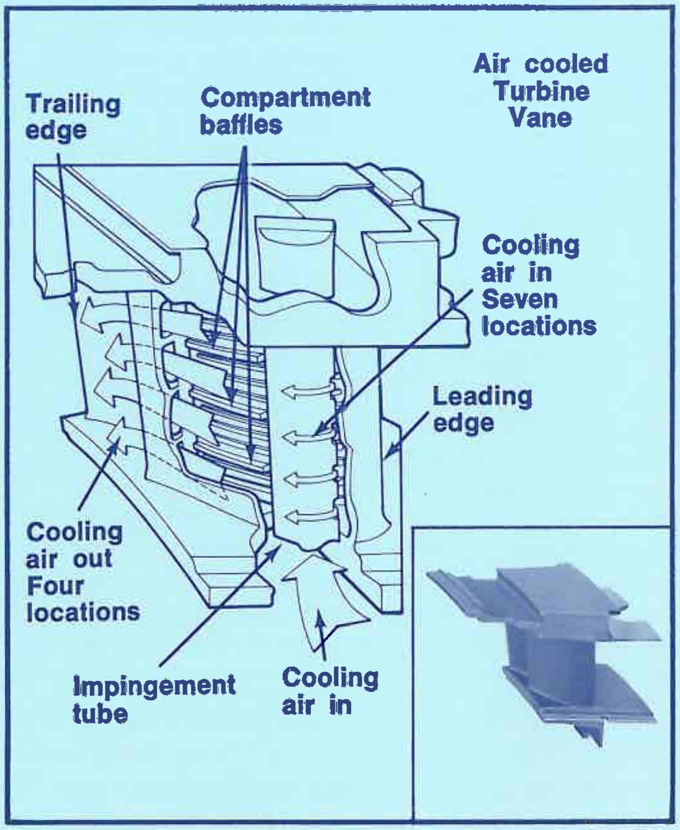

Figure 3. Air flow in air cooled turbine vane.

Blade and Vane Casting Technique

The blades and vanes of the air cooled 501-K are made by the precision investment casting process that is commonly called the "lost wax process." In this process, dimensional precision is carefully maintained to permit many surfaces to be used exactly "as cast." This eliminates most of the machining of the stock that would otherwise be required, and reduces cost. For instance, a smooth cast surface of 85 microinch permits air foil surfaces to be used "as cast," and the intricate core passages of the blades and vanes are similarly formed to precise shapes and dimensions. The process works as follows . . .

The precision investment casting process begins with a die, usually machined from steel or aluminum, into which wax is injected to form a pattern which is essentially a replica of the desired finished casting.

When intricate internal passages are required, a preformed ceramic core, such as shown in Figure 4, is placed in the pattern die before wax injection. This becomes encapsulated in the wax as illustrated in Figure 5. The core protrudes from the wax pattern in one or preferably more locations.

Individual wax patterns are assembled into clusters with connecting wax shapes which later form ducts in the mold through which molten metal travels to reach the end cavities.

A mold is fabricated around the wax cluster by alternate applications of ceramic slurries and dry "stucco" materials. Wax is then melted from the mold leaving the desired precision cavities. Ceramic cores remain properly located in the cavities by the core protrusions from the wax patterns which are firmly embedded in the mold wall.

The metal is poured into the mold and allowed to cool after which the castings are cut free from the clusters. The internal passage ceramic cores are removed from the casting by a chemical leach process and finally, the finished castings (Figures 6 and 7) are heat treated to obtain the desired mechanical properties.

There are 13 separate inspections of the blades and vanes to insure continuous, maximum quality control. Inspections are performed by highly sophisticated x-ray equipment that examines the cast internal surfaces of the blades and vanes for the slightest variation from the specified tolerances. Smoothness and consistency of the alloy surfaces are also accurately controlled.

The precise, consistent contours these intricate techniques achieve and the quality control they demand are important production and performance factors.

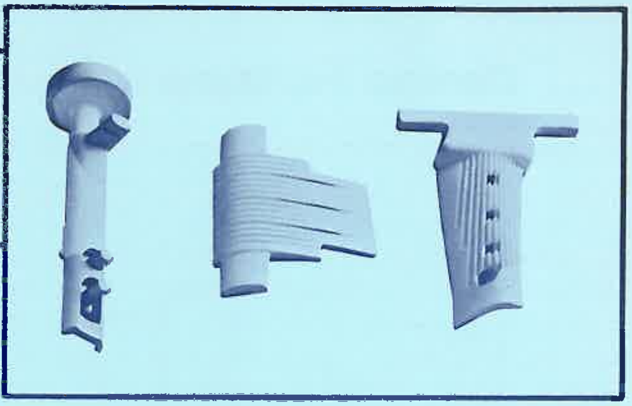

Figure 4. Ceramic core.

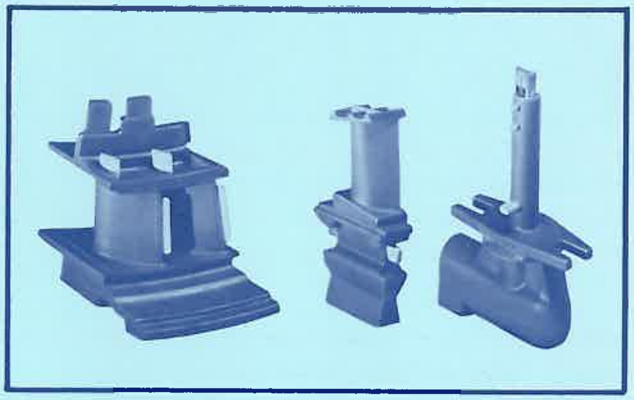

Figure 5. Wax pattern with incapsulated ceramic core.

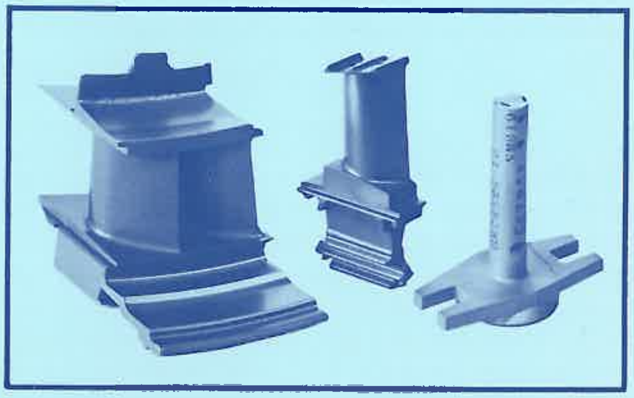

Figure 6. Finished casting.

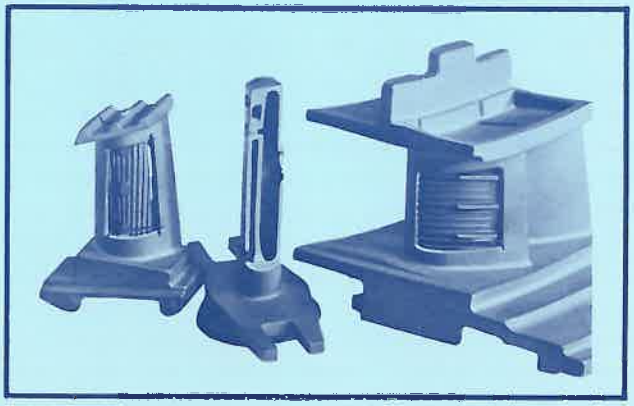

Figure 7. Cutaway showing internal passages formed by ceramic core.

Material Selection Standards

The 501-K gas turbine engine is configured for both a normal industrial and a marine environment application. The selection of alloys for the blades and vanes is, of course, dependent upon the mechanical properties of the alloys with respect to yield strength, stress rupture life, fatigue strength, thermal shock resistance, oxidation resistance, and hot corrosion resistance.

Proper utilization of these properties requires an accurate determination of the turbine blade and vane operating environment with respect to the time/temperature relationships, mechanical stresses, and turbine inlet gas chemistry. The maximum expected design stress levels and metal temperature patterns must be determined for the blades and vanes, based on the desired duty cycle and service life.

Materials under consideration are evaluated in relation to yield strength versus temperature, rupture life versus stress, and fatigue life which is derived through a complex stress analysis including both low cycle (engine start-run) and high cycle (vibratory stress) fatigue factors. The metal selection is also contingent on its relative resistance to thermal shock, oxidation, and hot corrosion.

The final selection of the alloys is made with respect to all these factors, considering the following priorities: the blades are highly stressed, and high hot strength and heat resistance are required. For marine service, the blades must exhibit excellent hot corrosion resistance. The vanes must operate at a high metal temperature but are lightly stressed; however, they are subjected to thermal shock. Oxidation and hot corrosion resistance are predominant requirements of the vanes. The metals selected for the air cooled blades and vanes of the 501-K engines, therefore, are nickel base and cobalt base high temperature alloys. For marine service special corrosion-resistant properties are added.

The ALPAK Sulfidation Protection Process

Sulfidation is a form of metal corrosion that attacks air foil sections in gas turbine engines, especially in the high temperature nickel base alloys. Corrosion takes the form of accelerated oxidation of surface metal, and characteristically causes surface roughening followed by blistering and eventually splitting and flaking of the oxide particles. Corrosion is usually most severe at the leading and trailing edges of the air foil.

Sulfidation is caused by the presence of sodium and sulfate ions in the form of sodium sulfate and sodium chloride in sea water, sulfur in fuel, sodium sulfate in cleaning solutions, sulfur dioxide in the air, and sulfur bearing particulates suspended in the air from industrial wastes. At high turbine temperatures, sodium sulfate can react with the oxide scales on certain turbine blade and vane alloys, causing the metal oxide to become unprotective. Once the protective oxide film has been disrupted, the sodium sulfate reacts rapidly with the base material to form sulfides and large amounts of sodium oxide. Sodium oxide prevents reformation of a protective metal oxide scale, permitting the corrosion process to continue at an accelerated rate.

A gas turbine engine can be designed to allow for corrosion of the blades and vanes necessitating their replacement at intervals indicated by the extent of corrosion and decline in performance. This practice is not unusual in the manufacturing of solid blades and vanes, although the greater metal thickness involved adds weight to the engine and increases fuel consumption due to the need to operate at lower temperatures.

Extensive experimentation was conducted by Detroit Diesel Allison to produce a coating that would extend the endurance life of 501-K turbine blades and vanes by providing sulfidation protection at elevated firing temperatures. A patented, proprietary General Motors process known as "ALPAK" was developed as a result of this prolonged research effort.

The ALPAK process consists basically of the diffusion of aluminum into the blade and vane metal surfaces. The aluminum penetrates the surface to form a protective coating that is .002 to .003 inches thick (.050 mm to .076 mm). This coating assists the base metal in forming a "self-healing" oxide film which resists further oxidation of the surface and, particularly, the attack of airborne sulfate materials from sea salt or industrial atmospheres.

In applying ALPAK, the parts are first cleaned with an abrasive material and placed in a closed metal retort surrounded by a dry powdered mixture of aluminum, aluminum oxide, and ammonium chloride.

Air is then purged from the retort with an inert gas, and the retort is heated in a furnace to approximately 1500 degrees F (815°C). This process deposits a smooth aluminum coating on the surfaces of the parts which are subsequently heated in a controlled atmosphere furnace to 2000 degrees F (1093°C). This diffuses the aluminum into the surfaces to produce the protective coating of the desired depth.

Since the development of the ALPAK process, experience has shown that it provides excellent protection for the 501-K engine during operation at high turbine inlet temperatures in unfavorable environments and with high sulfur content fuels. Engine efficiency is maintained without the increase in weight, size and fuel consumption associated with large blades and vanes that are intentionally allowed to corrode.

Continuing 501-K Improvement

Continuing engine development programs at Detroit Diesel Allison are supported both by in-house and field service component improvement programs, to increase performance and service life. Currently engines assigned to research programs in which experimental and production parts are subjected to an exhaustive variety of operating condition tests, such as accelerated endurance, sulfidation, sulfur bearing fuel corrosion, burner generated carbon erosion, sand and dust laden inlet air, and parts qualification tests.

Thousands of test hours have been accumulated during component improvement programs to investigate new alloys for improved service life, characteristics of special castings and advanced turbine cooling techniques for improved performance.

As the findings of these development programs are authenticated and incorporated in engines, they are made immediately available to all 501-K users. As new components are developed they are purposely designed to be interchangeable. The Allison 501-K engine is, therefore, not subject to obsolescence. This on-going Detroit Diesel Allison engine support program will insure that new and updated engines will continue to increase in horsepower with lower specific fuel rates without sacrifice of reliability.

Requests for reprints of this article are welcomed by the Detroit Diesel Allison Division. Requests for speakers on the subject of gas turbine engines and air cooled turbine blades and vanes will be given every consideration.

The Factor That Makes The Difference In Allison 501-K Gas Turbine Engines

Detroit Diesel Allison
Division of General Motors Corporation

Indianapolis, Indiana 46206

SA 1410B 5M 7/76 LITHO IN U.S.A.