TRIBOLOGY IN LIQUID OXYGEN OF SIC/SIC CERAMIC MATRIX COMPOSITES IN CONNECTION WITH THE DESIGN OF HYDROSTATIC BEARING

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ABSTRACT

This paper aims with the characterization of ceramic matrix composites for bearing applications in LOX. First, compatibility tests have been performed to assume the safety and feasibility of further research operations. Then tribology tests were made on a pin-on-disc apparatus using LOX as working environment. The measurement of friction and wear allowed a comparison between different kinds of CMC and steel 440C materials. As a logical approach, a real geometry test rig is now being built up. The design of a hybrid journal bearing has been finished and the manufacturing of the rig components started.

1. INTRODUCTION

SiC-ceramics reinforced by SiC fibers belong to the class of ceramic matrix composites (CMC). This kind of materials has been used successfully in bearing application for pumps in power plants [1]. In sliding conditions and with water of up to 160°C as the lubricant in pumps of power plants, the pair of conventional SSiC ceramic running against the CMC material SiC/SiC can sustain about three times higher loads than any other experienced couple of materials. Another potential application is now being considered namely journal bearings for pumps in cryogenic rocket engines for future reusable launch vehicles (RLV), where obviously lifetime of mechanical components is a critical issue. In particular, journal bearings on the basis of ceramic materials could replace ball bearings presently in use. Improved stiffness and damping properties, reduced wear, increased reliability and no limitations in speed x diameter would be some of the expected advantages [2]. This topic has to be developed further mainly on the experimental side.

So, in a first step, an exhaustive test program has been performed to qualify several kinds of CMC materials produced by chemical vapor infiltration (CVI) technique to use them safely in liquid oxygen (LOX). These tests included ageing and impact tests as well as auto-ignition behavior and friction experiments in liquid oxygen.

In a second step, the design and the manufacture of a hydrostatic test rig for radial bearings in LOX has been started. An own built computer program has been used for the bearing design. The flowchart of this program is based on the classical Reynolds equation solved to compute the fluid film characteristics, which are derived from the pressure field. A parametric study has been performed based on a journal bearing of 70 mm diameter and a 0.5 L/D ratio. Considering LOX and LN2 properties, the computation of results permits to determine other geometrical dimensions like clearance, orifice diameter, chambers area and number, etc.

2. CMC MATERIALS

MAN Technology has developed the manufacturing of Ceramic Matrix Composites (CMC) for applications in space technologies [3-5]. On the basis of C- and SiC- fibres, CMC materials with a high standard of properties have been developed. The mechanical performance is based on the high tensile strength of the fibres (>2000 MPa) and their tensile strain up to 2.0% as well as on the fibre pull-out mechanism, which allows the fibres to bridge the widening matrix cracks.

The essential properties of CVI derived materials can be described as follows:

- tensile tests show pseudo-plastic behaviour and a maximum strain of 0.5 to 0.8%, more than ten times that of conventional ceramics.
- strain controlled low cycle fatigue tests show high dynamic loadability; at a starting stress level of +/-80% of the material strength, 8 million cycles have been reached.
- single-edge notch bend tests show, compared to conventional SiC, a high crack resistance at a level of cast iron.
- thermal shock testing in a C_2H_2/oxygen flame show extreme mechanical reliability and, finally,
- the material is notch insensitive so that micro-cracks, porosity or surface scratches do not decrease its mechanical performance.

Table 1 gives hereafter some of the essential mechanical data.

Table 1. Properties of SiC matrix composites with 2D orthogonal fibre reinforcement.

Property	Unit	CVI-SiC/SiC	CVI-C/SiC
Fibre content	Vol%	42-45	42-47
Density	g/cm^3	2.3-2.5	2.1-2.2
Porosity	%	10-15	10-15
Tensile strength	MPa	280-340	300-380
Strain to failure	%	0.5-0.7	0.6-0.9
Young’s modulus	GPa	190-210	90-100
Bending strength	MPa	450-550	450-500
ILSS	MPa	45-48	44-48
Coefficient of thermal	$10^{-6}K^{-1}$ $\parallel$	4	3
Expansion	$\perp$	4	5
Heat conductivity	$Wm^{-1}K^{-1}$ $\parallel$	20	15
	$\perp$	10	7

As a summary of above characteristics, one can say that the essential advantage of CMC compared to conventional ceramics is its reliability and lack of brittle failure.

The high strain to rupture and crack resistance are of great advantage for the mounting of a CMC shaft sleeve by simple shrink fitting it on metal. The difference in thermal expansion coefficients can result in high tensile (hoop) stresses, which conventional ceramics are not able to sustain reliably. In tests, it has been shown that a SiC/SiC sleeve shrink fitted on Inconel 718 can work on temperature changes up to 200 K with a (calculated) permanent hoop stress of about 150 MPa.

3. TEST CAMPAIGNS

3.1 Compatibility tests

Preliminary tests have been performed to evaluate the compatibility of materials to LOX. Three types of tests demonstrated the compatibility: Ageing, impact and ignition tests.

Ageing:
Tensile, bending and inter-laminar shear strength of C/SiC and SiC/SiC was determined at room temperature with two, six and two samples respectively after 10,5 hours of ageing in liquid oxygen. Compared with the results of reference samples of the same production lot there was no observable difference in any of the measured strengths.
A bending test with C/SiC under –196 °C showed no influence of the bending strength on temperature [6]

Impact:
This test was performed according to the ASTM-Standard D 2512-95. A disc of 20 mm diameter and 1.35 mm thickness is covered with liquid oxygen. The impact of a hammer of 1 kg from a height of 1 m (corresponding to 100 J of energy) shows either ignition or traces thereof or has no effect of that kind. 20 of such impacts have to be observed on 20 samples.
The test gave no indication of any ignition.

Ignition:
The French standard NF 29-763 determines the temperature of ignition of a material under the following conditions: 0.5 g of the powdered sample of the material is slowly heated from ambient temperature up to 550°C in pure oxygen under a pressure of 120 bar (12 MPa). The temperature and pressure of the autoclave system is monitored and indicates in a very sensitive way any ignition process. Materials tested by this standard are classified in five groups following the temperature of observed ignition. The basic constituents of C/SiC and SiC/SiC were tested separately: chopped C-fibres (T300 from Torayca), chopped SiC-fibres (Tyranno from Ube Industries), SiC powder derived from the CVI-process of CMC manufacturing and powder of amorphous SiC, derived by pyrolysis of a polycarbosilane. The latter is used to fill the open porosity of the CMC-material in the above mentioned application of bearings in pumps. The test showed only the C-fibres with auto-ignition at 437°C. All other samples did not ignite. Thus it can be concluded that SiC/SiC, including the filling of its porosity, can safely be applied in liquid oxygen. Tests to determine wear and friction coefficients in pin-on-disc equipment followed and are described in the next paragraph.

3.2 Friction tests

The relevant tribological experiments have been performed on a pin on disk tribometer, which is installed at the University of Liège inside a specific test zone. This test zone is fully equipped with up to date data acquisition systems which record experimental results but also monitor and control all the lines conveying the fluids (LOX, LN2, GN2, GHe) to the test benches.

The type of contact used for testing the CMC materials was a flat on flat contact. The diameter of the pin was 8 mm. The load was applied by a dead weight, which could be varied between 1 daN and 14 daN, while the sliding speed could be varied between 1 and 5 m/s [7].

Some results with their corresponding test conditions are presented hereafter. Concerning the friction coefficient, the data acquisition system used to monitor it allows to have a more detailed information in addition to the classical value of the mean friction coefficient [8]. In fact, a data treatment gives the friction coefficient distribution during a test. According to this approach, in fig. 1, we can make the distinction between the running-in phase, where the friction coefficient is distributed around 0.6 and the steady state, where the friction coefficient is distributed around 0.4.

Fig. 2 and fig. 3 present the behavior of different kinds of CMC materials compared to the 440C stainless steel currently used in aerospace propulsion. Fig.2 shows clearly that the mean friction for CMC materials is almost half that of stainless steel. As to fig.3, it exhibits that the wear ratio calculated using Archard's law is around 100 times less for CMC than for 440C stainless steel.

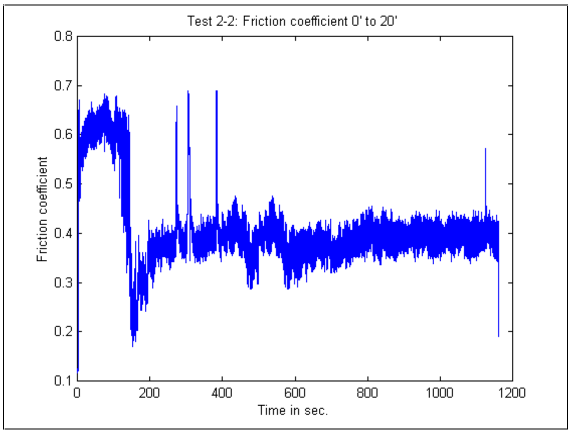


Figure 1.1: Friction trace with two main values for the friction coefficient
Pin CMC2/Disc SSiC; P=2.76 MPa – V=0.5 m/s

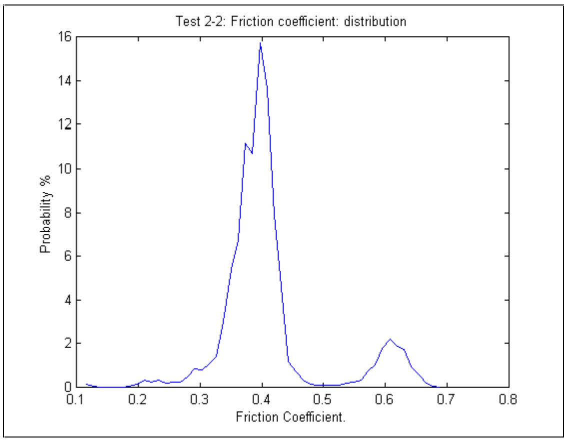
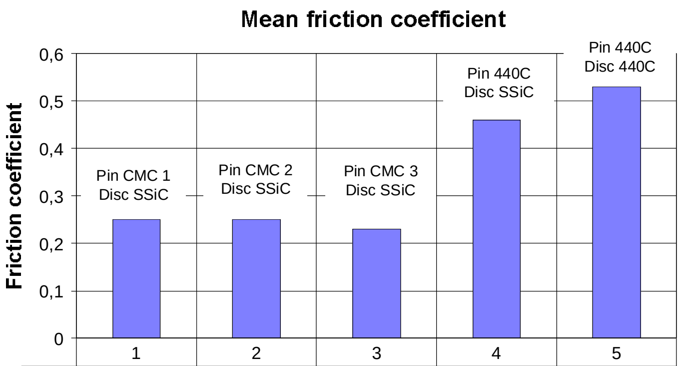


Figure1.2: Statistical distribution of the friction trace
Pin CMC2/Disc SSiC; P=2.76 MPa – V=0.5 m/s



	1	2	3	4	5
Série1	0,25	0,25	0,23	0,46	0,53

Figure 2: Comparison of friction coefficients
CMC vs. stainless steel 440C – P = 2.76 MPa – V = 4 m/s

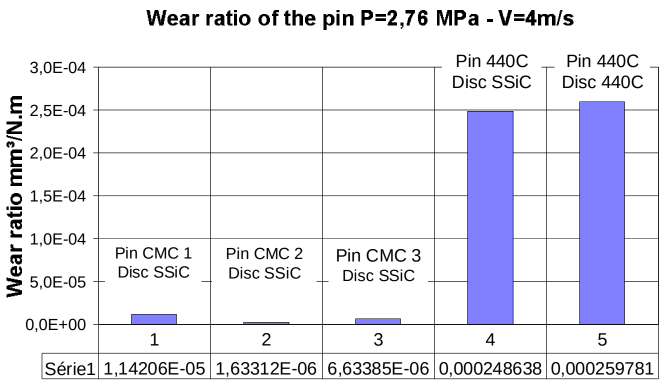


Figure 3: Comparison of wear ratios
CMC vs. stainless steel 440C – P = 2.76 MPa – V = 4 m/s

4. DESIGN OF HYBRID BEARINGS

The design of a hybrid journal bearing geometry is based on the fluid mechanics theory adapted by O. Reynolds to thin film lubrication. A journal bearing is simply made of a shaft rotating in a circular sleeve filled with lubricant. This very simple geometry remains nevertheless very sensitive to vibrations and the load capacity is limited when using low viscosity fluids like cryogenics. A technological improvement consists then to inject the fluid under pressure through calibrated recesses into pockets machined in the sleeve. This type of feeding adds a dissipative effect, which increases the damping coefficients, while the load capacity is improved by the supply pressure as well as the stiffness coefficients. This particular geometry of bearing is called hybrid because the load capacity is partly due to hydrodynamic effects, like in a classical journal bearing, and simultaneously to the external pressure applied through correctly designed recesses.

This approach consists first in using a computer program based on the Reynolds equation (1), simply written as follows [9][10]:

Equation (1)

$$\frac{\partial}{\partial x}\left[G_x h^3 \frac{\partial P}{\partial x}\right]+\frac{\partial}{\partial z}\left[G_z h^3 \frac{\partial P}{\partial z}\right]=\mu\left(\frac{U}{2}\frac{\partial h}{\partial x}+\frac{\partial h}{\partial t}\right)$$

In which we find:

P	the fluid pressure (Pa)
h	the film thickness (m)
x,y,z	the coordinates
t	the time (s)
G_x, G_z	the turbulence coefficients given by (2)
U	the sliding speed (m/s)
ρ	the mass/volume ratio of the fluid (kg/m^3)
R_e	the local Reynolds number $\rho Vh/\mu$
μ	the dynamic viscosity (Pa s)

Equation (2)

$$\frac{1}{G_x}=12+0.0136 R_e^{0.9} \quad ; \quad \frac{1}{G_z}=12+0.0043 R_e^{0.96}$$

The right hand side member of equation (1) includes the geometric influence of the edge $\delta h/\delta x$, the viscosity of the fluid μ and finally the non steady-state term in squeeze film $\delta h/\delta t$. This last one is influent on the calculation of damping coefficients, which lead, in association with stiffness ones, to the dynamic study.

Equation (1) is then solved using the finite difference technique in which the definition of boundary conditions is essential. These are the pressure on both sides of the journal bearing and inside the pockets, which depend on the recess design. In practice we calculate, for each pocket, the inside pressure by equilibrating the flow that goes in through the restrictors with the flow that goes out and feed the fluid film. An example of such a result is shown in figure 4, illustrating an academic case of study with six capillaries. The geometry is based on a 70 mm shaft, a 0.5 shape ratio and parametric values for other dimensions like in [11], LOX and LN2 data being finally considered to describe the "lubricant" behavior [12]. Figure 4 shows the pressure field calculated for a high value of the shaft eccentricity, 0.9. One can see a high feeding pressure at the opposite of the load, in connection with a parabolic peak of pressure located on the smooth surface, between the two pressurized recesses. The other pockets, in the unloaded zone, are nevertheless depressed by the film surrounding and by the pressure loss in restrictors.

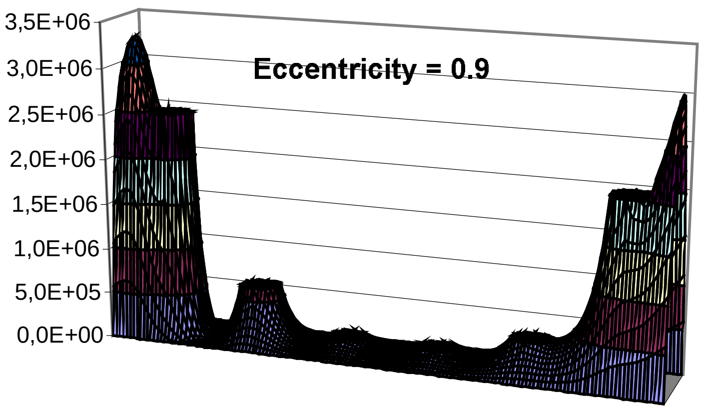


Figure 4: Pressure field in the sleeve

At the opposite of what is shown above, in the case of a small eccentricity of the shaft in the sleeve, no pressure peak remains visible between the feeding pockets and the role of restrictors is then predominant. This is particularly of importance when considering stability and resonant frequency of the shaft. A good design of restrictors will then assume an acceptable fluid flow in association with a significant pressure drop as soon as the shaft will leave its nominal position. The visibility of this being represented by high stiffness and damping coefficients.

After this brief presentation of the program, it can be used to evaluate loads and loss flows in future experimental working conditions at 10.000 rpm. The results hereafter concern the academic geometry corresponding to figure 4 and show major influences of the radial clearance and restrictors design. As usual, the load capacity is increased by a reduction of the clearance (figure 5) but generates manufacturing difficulties so that a nominal value must be kept in practice. Furthermore, the real parts will have to be measured before the first run of the test rig in order to then use our model as precisely as possible to check the adequacy of the theoretical approach with experimental results. Figure 6 shows that the advantage of keeping the clearance small is underlined by the reduction of LOX consumption. It is unfortunately not the case when considering the design of restrictors because, as shown in figures 7 and 8, an increase of their main dimension (i.e. surface) generates a higher load capacity of the bearing but also more important flows, that must then be managed by the test rig environment.

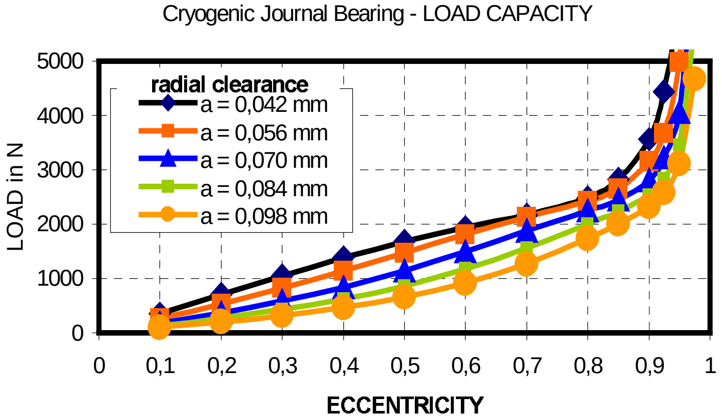


Figure 5: Influence of the radial clearance on the load

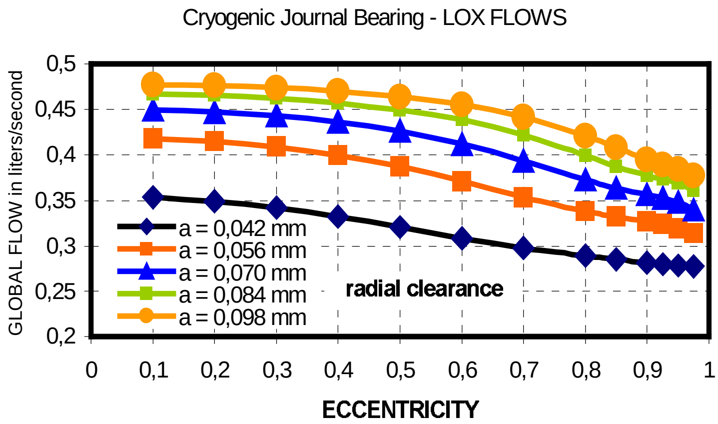


Figure 6: Influence of the radial clearance on recess flows

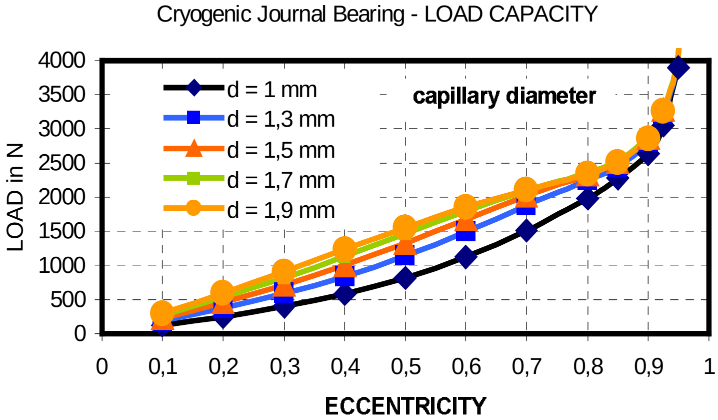


Figure 7: Influence of the capillary diameter on the load

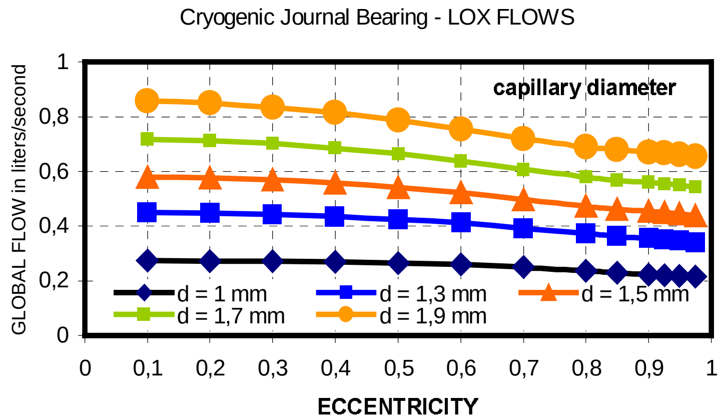


Figure 8: Influence of the capillary diameter on recess flows

After this theoretical approach, the test matrix has been developed and the associated test rig manufactured. The tests will provide results concerning materials [11] as well as concerning the adequacy of using such a model to design a cryogenic journal bearing. We planned to perform tests in steady-state conditions as well as start and stop periods, which have also been simulated with our program. We observe for example that the use of bigger restrictors decreases considerably the influence of the rotational speed on the bearing characteristics.

5. CONCLUSIONS

The idea to use slide bearings under high load conditions in cryogenic turbo pumps was followed up on the basis of using sintered silicon carbide (SSiC) and the ceramic matrix composite (CMC) SiC/SiC as bearing materials. The results of the tests proved the compatibility of these ceramics with liquid oxygen. In pin-on-disc tests a reduced friction coefficient under mixed friction conditions compared to a standard metallic material could be shown. Furthermore the measured wear with the ceramic materials is two orders of magnitude smaller than that of the tested metallic system. The design of a test rig for slide bearings lubricated with liquid oxygen has been completed and its realization is nearly finished. All results so far achieved indicate that a ceramic journal bearing system based on SiC/SiC composite material as shaft sleeve component and SSiC as tribological partner will yield the advantages in cryogenic bearings for turbo pumps of future propulsion systems, which have been mentioned in the introduction. Especially the low wear measured under mixed friction indicates that increased lifetime and extended reusability of such ceramic bearings can be expected.

6. REFERENCES

[1] W. Kochanowski, P. Tillack, New Pump Bearing Materials Prevent Damage to Tubular Casing Pumps, VDI-Berichte No. 1421 (1998), p. 227-242

[2] G. Grease, R. Lyda, J. Park, A Minick, Design and Test Results of an Advanced Liquid Hydrogen Turbopump, 35th AIAA/ASME/ SAE/ASEE Joint Propulsion Conf., Los Angeles (1999), paper AIAA 99-2190

[3] M. Bickel, M. Leuchs, Ceramic Matrix Composites – A New Material in Tribological Applications, MAN report, November 1997.

[4] Mühlratzer, K. Handrick, H. Pfeiffer, Development of a new cost-effective ceramic composite for re-entry heat shield applications, 46th Int. Astronautical Congr., Oslo, (1995), paper IAF-95-I.3.01

[5] M. Dogigli, H. Weihs, K. Wildenrotter, H. Lange, New High-Temperature Ceramic Bearing for Space Vehicles, 21st Int. Astronautical Congr., Rio de Janeiro, (2000), paper IAF-00-I.3.04

[6] Fröhlich, H. Krings, Development of an Internal Oxidation Protection System for C/SiC, Final report on the FESTIP program Technology Development in Materials for Reusable Launch Vehicles, Doc. No. FTM-MAN-FIR-4000-001

[7] J.L. BOZET and al., Tribologie en Oxygène Liquide, Matériaux et Techniques, N° Hors Série, SIRPE, 1999.

[8] J.L. BOZET, M. NELIS, The regularity of the friction coefficient, different means of characterization, Eurotrib, 1993.

[9] J. FRENE, D. NICOLAS and al., Paliers et Butées, Collection des Etudes et Recherches d'Electricité de France, Eyrolles, 1990.

[10] V.N. CONSTANTINESCU, Basic Relationships in Turbulent Lubrication and Their Extension to Include Thermal Effects, Journal of Lubrication Technology, April 1973, 147 – 154.

[11] J.K. SCHARRER, J. TELLIER and R. HIBBS, A Study of the Transient Performance of Hydrostatic Journal Bearings: Part II – Experimental Results, STLE/ASME Tribology Conference in St. Louis, Missouri, October 14-16, 1991.

[12] NIST Standard Reference Database 12, Copyright 1986-1992 by US Department of Commerce.