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Printed in U.S.A.

35 YEARS OF OPERATION WITH ROLLS-ROYCE MARINE PROTEUS GAS TURBINES IN SWEDISH NAVY FAST SURFACE ATTACK SHIPS.

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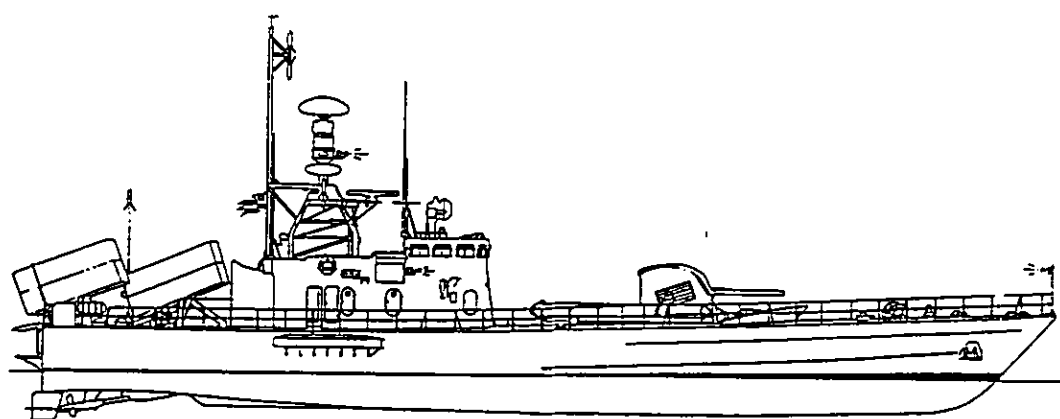


Fig. 1. The Swedish Navy NORRKÖPING Class Missile Boat.

ABSTRACT.

This paper covers 35 years of operation with the ROLLS-ROYCE Marine PROTEUS Gas Turbine in the Swedish Navy SPICA class Torpedo Boats and the NORRKÖPING class Missile Boats.

54 installed PROTEUS Gas Turbines in 18 boats have accumulated nearly 300 000 running hours. The service is intended to continue until year 2010.

The paper describes:

- Experience from operation.
- Technical problems and their solutions.
- Major modifications.
- Life extension program.

- Problem areas.
- The future of the PROTEUS within Swedish Navy.

The Swedish Navy operation of PROTEUS engines in fast surface attack ships is demanding and the environment is harsh. This causes great strain to the entire machinery.

With the Gas Turbine Propulsion new Ship maneuvering technique had to be developed and adopted.

Initial installation and engine problems had to be cured.

Throughout the years several technical problems have turned up and been solved.

The largest number of serious engine damages has been Power degradation and broken Compressor or burnt Turbine

Blades and Vanes. Mainly as a result of a fouled Compressor, incorrect Bleed Valve setting or corrosion.

Next largest engine problem has been vibration. In the early days engine related but nowadays generated by the installation of other equipment in the ship.

All efforts laid down by involved personnel has greatly contributed to improve the reliability of the engine and its installation.

New problems will certainly show up by age and changed operational procedures, thus calling for a continued improvement work.

Spare parts accessibility will be the limiting factor for future PROTEUS operation. Therefore cooperation with ROLLS-ROYCE and the remaining operators in Spare Parts production and for exchange of Spare Parts is essential.

HISTORICAL BACKGROUND.

First attempts.

Gas Turbines as main propulsors in naval application were considered early in Sweden.

During the early 1950's trials with both British and Swedish Gas Turbines were carried out in Torpedo Boats.

In the late 1950's the then 3500 hp (2600 kW) BRISTOL PROTEUS Gas Turbine was marinized and became available. One PROTEUS was installed as a replacement for one of the diesels in the 130 ton Torpedo Boat T101.

The tests started in 1960 and gave a great deal of experience for the design of the SPICA class Torpedo Boat.

The first operational Gas Turbine driven warship in Sweden, the SPICA class Torpedo Boat.

With the above tests as background, a series of six SPICA Torpedo Boats were designed and built.

The displacement was 210 tons, length 43 m and top speed 40 knots. Three PROTEUS Gas Turbines were arranged in a COGOG machinery with each PROTEUS driving a KAMEWA Controllable Pitch (CP) Propeller via ALLEN Primary and Main Reduction Gears. The armaments were 53 cm Torpedoes for surface attack missions and a multipurpose 57 mm BOFORS Gun for self defense. Other missions were Mine Laying, escorting and patrolling.

The SPICA boats were delivered to the Swedish Navy 1966-1968 and remained in service until 1985-1987. A total of 80 000 Gas Turbine running hours were accumulated. All PROTEUS Gas Turbines were retained and modified for use in the next generation of boats.

The first boat in the series, T121, HMS SPICA, is now exhibited in the Carlskrona Maritime Museum.

Second generation, the NORRKÖPING class Missile Boat.

Based on the experience gained from SPICA another twelve Torpedo Boats, the NORRKÖPING class, were designed and built. The same machinery arrangement was used. Many of the problems on the SPICA class were eliminated. The ALLEN Main Reduction Gears were substituted by gears from ZAHNRAD-FABRIK FRIEDRICHSHAFEN.

The displacement is 240 tons, the length 44 m and top speed 40 knots. The crew is a total of 30 with 15 officers and 15 conscripts.

At delivery 1974-1976 the NORRKÖPING class was designated Torpedo Boats with armament and missions similar to SPICA. In 1983-1984 SAAB Missiles RBS 15M were installed and they were renamed as Missile Boats. Figure 1.

The Machinery.

The machinery consists of three similar drive lines. Fig. 2. A common Air Intake with water separating louvers supplies air to the Gas Turbines. Three separate exhaust pipes exit in the ships stern.

Each PROTEUS is fitted with an ALLEN primary gear and drives the ZF Main Reduction Gear through a drive shaft. The propeller shaft is directly connected to the Main Reduction Gear, where all the propeller thrust is taken. The Main Reduction Gear also carries the CP propeller control system.

The Machinery Control room is equipped with aircraft style instrumentation for watchkeeping. Three separate Throttles operate the individual Gas Turbines and CP Propellers through Cam Controllers, controlling Compressor speed and Propeller pitch.

The crew can operate one drive line, two in any combination or all three together.

ROLLS-ROYCE product support.

From the very first trials, through the design, build and commissioning of the SPICA and NORRKÖPING series until today's operations, staff from BRISTOL and later ROLLS-ROYCE have assisted and supervised the Swedish Navy. The Product Support and Spares Supply organizations have given excellent support, mainly arranged as regular Customer Service Liaison Meetings.

VOLVO overhaul and repair Support.

In 1966 the Swedish Navy contracted the Air Force Central Workshop in Malmslätt to arrange for complete overhaul, repair and testing facilities for PROTEUS and its accessories. In 1968 the resources were transferred to FFV in Arboga and in 1991 to VOLVO, still in Arboga.

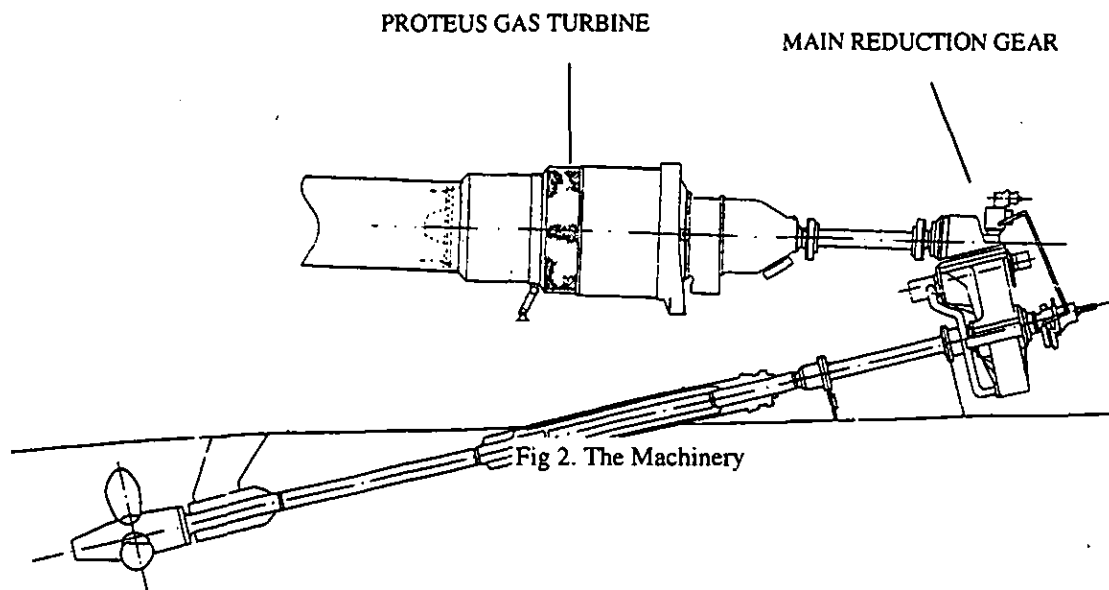


Fig 2. The Machinery

The national resource has been very important to the PROTEUS operations with on board maintenance, modifications programs necessary for correcting operational problems and technical support to and education of Swedish Navy personnel.

EXPERIENCE FROM OPERATIONS AND MAINTENANCE.

Handling related problems.

Salt Water into Air Intake.

In moderate winds sea water sprays over the air intake. Thus salt water droplets enter the intake. At heavy sea states and strong winds the sea water splashes over and into the intake. The problem here is not the droplets but "green sea" running into the engine air intake and over the entire engine.

The result is heavy salt deposits in the compressor and severe hot corrosion in the turbine. Also atmospheric corrosion takes place internally and externally. Although never reported there are signs that the "green sea" ingestion results in compressor surge. So far there are no indications of thermal chock.

Repeated discussions with the maneuvering officers to convince them to avoid the most severe situations. Detergent Compressor running wash technique helps to restore performance.

Use of inhibiting fluids internally and externally at standstill periods retards corrosion.

Corrosion Protective Coating on gas path and other critical surfaces is continuously improved.

Salt Water Intrusion in Exhaust.

The engine exhaust pipes are nearly horizontal and opens to atmosphere in the stem. Although remotely operated exhaust flaps are fitted they are left open to allow for forced cooling air exit at idling and after shut-down.

In worst cases large amounts of water find its way into the exhaust thus shorting the thermocouples and shutting down the engines.

Today the officers on the bridge have learned how to maneuver the Ship to avoid the salt water intrusion.

Ground touches and collisions with floating or submerged Logs.

When maneuvering at high speed in the narrow water of the Swedish archipelago ground touch is a frequent problem. There are also frequent collisions with semifloating or submerged logs, lost at transportation between the countries round the Baltic sea.

The resulting damages can be anything from a damaged or lost propeller to bent propeller shaft, broken main reduction gears and housings, turbine blade to housing rubbing and broken power turbine intermediate shaft.

Installation related problems.

Fuel Contamination.

Contaminated Fuel has caused severe problems. SPICA had inadequate filtration capacity. The filters clogged quickly and

hence stopped the Gas Turbines. To combat this new filters were installed on NORRKÖPING and better fuel handling both at land and on board was implemented.

Despite frequent removal of sediment and water, bacteria and fungus can grow in the ships tanks. This is counteracted by adding a biocide to the fuel.

Engine to Main Reduction Gear Alignment.

The existing design of the rear engine mount does not allow the engine centerline to be maintained at thermal expansion of the engine. As the engine grows, radially and axially, from the fixed front trunnions, the rear mounting bracket centerline travels backwards and upwards. This will raise the engine centerline at the rear end, lower the front end and lower the output flange.

The reason for existing design is the shock loading capability of the Air Intake Housing where the engine rear trunnion is fitted.

This might be the explanation to many vibration problems never explained earlier.

The Swedish Navy is looking into the possibility of installing the rear mount in a way to keep the alignment throughout the entire operating envelope.

Vibrations.

The engine and its installation has always experienced vibration problems.

Early in the program the delivery test acceptance criteria were generous. Engines delivered with high, but accepted, levels often gave unacceptable vibration levels in service. Modified assembly methods, tighter balancing and vibration criteria at delivery together with use of vibration analysis equipment in service has greatly improved the situation.

Since the only vibration monitoring equipment in the ship was installed on the Gas Turbines they were always believed to be the source for vibrations. When the first, simple frequency analyzer was introduced it gave the possibility to separate vibrations from power turbine, compressor turbine, drive shaft, propeller shaft and propeller blades.

The most frequent reasons for vibrations were:

- damage to or foreign objects in the Propeller the Drive Shaft
- improper alignment of the Gas Turbine to the Main Reduction Gear.

Introduction of in situ trim balancing reduced the Drive Shaft vibration problems.

The LAURUB Drive Shafts initially installed were of a rubber elements design and required very frequent balancing. After installation of METASTREAM drive shafts with membrane couplings, drive shaft related vibrations are very rare. The technique of trim-balancing is today next to obsolete.

The alignment technique has been improved by the use of laser equipment. The alignment requirements have also been reviewed.

The great vibration problems in the beginning resulted in cracks in exhaust annulus and in the Z-shaped mounting brackets that hold the turbine unit to the air inlet housing.

The rear mount installation redesign described above may also improve the vibration situation.

Gas Turbine Mechanical failures and problems.

Oil leakage at Primary Gear Output Shaft Seal.

Leaking at this labyrinth seal has two reasons:

- labyrinth surface wear from mechanical contact of stator and rotor due to vibrations
- over-pressurizing of gear carcass because of cracks in the membrane which normally separates the compressor discharge pressure from the oil and ventilation systems.

Primary Gear Main Bearings.

The ball retainer of the bearing in the front end of the output shaft has broken in several occasions.

All bearings were of the same manufacture. An investigation revealed that this has been believed to be a standard bearing. Therefore the bearing was purchased directly from the bearing manufacturer. This has worked well for many years until the bearing manufacturer change manufacturing process. The new roller cage did not withstand the actual forces and disintegrated.

Bearings are today supplied by ROLLS-ROYCE to their specification.

Primary Gear Planet Shafts.

The planet gears are fitted to babbitt bearing surfaces on the shafts. These bearings utilize the same oil system as the gas turbine.

Although the oil system has filters metal debris finds its way to the babbitt surface. The debris is embedded in the babbitt material and wear the planet gears.

A repair method includes grinding the planet gears to oversize and new babbitt material on the shafts to correct clearance.

Air Intake Screens.

The engine mounted air intake screens were originally made from mild steel. They corroded away and started to generate compressor damage.

New screens are manufactured from stainless steel.

Compressor Inlet Guide Vanes, broken or loose fixation.

The vanes broke or lost their fixation in the casing. Parts of or entire vanes entered the compressor with great damage as a result.

A modification where the vanes were fitted in vibration dampening rubber at both ends fully cured this problem.

Compressor Rotor to Stator rub.

Both compressor blades and impeller cut into the compressor housing. This happens at high shock loads or at severe vibrations.

The housing is restored by dressing and flame plating.

Compressor Rotor.

As with most compressor rotors of the "stacked drum" type without a central shaft PROTEUS has experienced a lot of problems at rotor build.

A specific torque tightening sequence has been developed to avoid problems at indicating and balancing.

Rotor Balancing.

Both partial and final balancing of compressor and turbine rotors has been subject to improvements of technique and closer tolerances. This has greatly reduced engine testing return rate and vibration related problems in service.

Compressor Diffuser Housing to Accessory Housing Bolts.

The bolts clamping the diffuser to the accessory casing were prone to corrode. At a certain corrosion level the bolts broke. When four or more bolts in line were missing the resulting air leak creates problem. An in-situ repair technique was developed.

ROLLS-ROYCE came up with bolts in corrosion resistant material that has cured this problem.

Diffuser Guide Vanes.

The original diffuser guide vanes from aluminum were severely affected by corrosion and wear from salt particles.

New guide vanes made from steel are much less prone to wear or corrosion.

Corroded Expansion Chambers.

The combustion expansion chambers were originally manufactured from mild steel. Heavy corrosion penetrated the skin allowing the compressor air to exit.

New chambers are manufactured from stainless steel.

Combustion Chamber Leakage.

The combustion chambers are prone to leak at the interconnecting tubes. A modification introducing longer tubes has improved the situation. But still the installation requires special attention to be air-tight. Even small vibrations or surges can cause the chambers to move enough to leak.

Mounting brackets crack due to vibration and strong tension when not installed properly. This adds to chambers freedom to move and leak.

These problems still has to be solved.

Flame Tubes.

The PROTEUS flame tubes suffer moderately from cracking and burning. A modification opened up the cooling holes in the flame tube head and has saved a lot of burning in that area.

A ceramic coating has been introduced to the Swedish Navy PROTEUS. This nearly doubles the service life.

Turbine Entry Duct and Liner.

The wear in this region has been transferred from the turbine parts to the combustion chamber parts. This is created by selection of material at salvage. The combustion chambers are easier to exchange compared to the turbine units. Improved vibration situation has reduced the overall amount of wear.

Turbine Blades and Vanes.

The original solid turbine inlet guide vanes have been replaced by hollow, cooled vanes. This together with cobalt based material has greatly increased the running hours.

Also new high pressure turbine blades have improved the situation.

An engine condition monitoring program that never allows the vanes and blades to deteriorate beyond the limit for salvage has had the most beneficial effect on engine service life and overhaul cost.

Turbine Rear Bearing.

Squeeze film dampening on outer bearing race has been tried on three engines in service. Squeeze film dampening has proved to reduce the effect of engine related vibrations. This does not preclude the need to make all efforts to remove the initial vibration source. Problems to fulfill Rolls-Royce requirements on machining of involved components has postponed the introduction of this modification.

Turbine Couplings.

The compressor turbine to compressor coupling and the power turbine coupling suffer from splines wear. No salvage method has proven effective yet.

Cracking Turbine Brackets.

The vibration problems resulted in cracking of the Z-shaped mounting brackets that hold the turbine unit to the air inlet housing.

This problem has nearly disappeared due to reduced vibration levels. In 1978 21 brackets were changed, during 1993 none and in 1994 one.

Cracks in Exhaust Annulus.

This was one of the major problems in the early days. The Exhaust Annulus crack propagation rate could be one mm per running hour. The exhaust units were changed at a total crack length of 1500 mm.

Welding in situ was tried as an emergency cure. During the year 1978 15 exhaust units were removed from service.

As the vibration situation has improved exhaust annulus cracking has reduced to near nonexistent. During 1994 two exhaust units were changed due to cracks. Max total crack length was 700 mm. The worst crack propagation rate was 0,3 mm per running hours.

Exhaust Diffuser Pipe Clamp.

The bolts in the exhaust diffuser pipe clamping ring broke. The diffuser pipe fell down within the exhaust pipe.

Improved bolt material and torque tightening technique eliminated this problem.

Broken Starter Shafts.

On the NORRKÖPING CLASS the starting air from the ROVER 90 hp (65 kW) gas turbine was substituted by air from the MTU 160 hp (115 kW) gas turbine. The increase in air flow and pressure caused the shaft between the air starter and the starter drive to break.

A restrictor in the starter air valve maneuvering system reduced the air shock wave and thus the shaft peak torque. Later the starter shaft was modified with torque pins that break at a controlled torque and are easy to replace.

The MTU gas turbine is now substituted by a diesel engine. The air starting system is at the same time changed to a computer monitored hydraulic system. This system will give smoother gas turbine acceleration and cranking speed above self-sustaining speed.

Fuel Cooled Oil Cooler.

The SPICA series had a Fuel Cooled Oil Cooler installed. The transmission of heat to the Fuel was found to be the reason to problems achieving full power in warm weather conditions.

On the NORRKÖPING class a Sea Water Cooled Oil Cooler was installed.

Fuel Control Units.

The Fuel Control Units (FCU) suffered from unstable settings, oscillating idling speed and leaking membranes. A lot of maintenance work was needed to change units and to set the engine parameters.

All these problem has been cured by improved material, build technique and clearance selection.

High Speed Shut Off Cock.

Frequently the High Speed Shut Off Cock (HSSOC) closed and thus tripped the engine during operation in heavy sea state. It was very annoying to lose engine power in severe condition. It was found that the HSSOC couldn't withstand the specified 9g acceleration. The trip occurred already at 2,5g.

Another problem was piston sticking in the sleeve. This prevented normal shut downs. The engines had to be stopped with the Low Pressure Shut off Cock.

Both problems has been cured by ROLLS-ROYCE-developed modifications.

Burners.

The fuel burners are of a simplex design. This leads to poor starting capability and heavy smoke at low power.

This is still a problem. An early introduction of duplex burners would have paid off several times by now.

Sticking Compressor Air Bleed Valves.

Salt and dirt introduced via the air intake causes the compressor air bleed valves to stick. This results in compressor surge.

Only remedy so far is frequent cleaning. Intake air filtration or at the least a device that keeps sea water from pouring into the intake is greatly needed.

Inconsistent Compressor Air Bleed Valve Settings.

The compressor bleed valve control valve is not consistent on speed setting. Modifications so far have not cured this. Speed monitoring by means of frequency relays have been tried with some success.

Bleed valve position indicators have been introduced to monitor the proper operation.

Exhaust Temperature Monitoring.

There has always been a 30-35 centigrade difference in exhaust temperature readings from engine test bed to ships installation. It has been discovered that the wrong type of thermocouples were

installed. They were too short and didn't reach past the exhaust pipe cooling shroud into the exhaust gas stream.

Correct type thermocouples are now installed and giving better temperature correlation.

The installation is modified to allow individual thermocouple readings. This will give the possibility to track hot or cold spots in the gas path as an early failure warning.

LIFE EXTENSION PROGRAM.

Six of the twelve NORRKÖPING class ships are currently modified for a life extension. The modifications to the PROTEUS and its installation are:

- New design on engine rear mount, to compensate for thermal expansion.
New, high pressure, compressor wash installation combined for crank soak and running wash operation.
Dry air installation for machinery protection during non-operational periods.
- Improved engine corrosion protection both internally and externally.
- Improved and extended instrumentation for more accurate performance calculations.
- Exhaust temperature indicator installation with individual T/C reading for tracking of Gas Path Hot or Cold Spots.
- Bleed valve position indicator system.
- New vibration monitoring system.
- Air starter changed to hydraulic starter as MTU auxiliary Gas Turbine is substituted by a Diesel Engine.

All equipment such as the Gas Turbines, Main Reduction Gears, METASTREAM drive shafts and instrumentation from the obsolete ships will be kept as spares. In many instances these are the only spares available for this out-of-date materiel.

PROBLEM AREAS.

Although the PROTEUS engine is of an old design it is reliable, easy and so far not so expensive to maintain. Yet not discovered problems together with spare parts accessibility can greatly affect the cost. In the worst case a lack of spares can stop future operation of the PROTEUS.

Spares, apart from consumables, are not under production with ROLLS-ROYCE. Starting production of spares is very difficult:

- The raw materiel is outdated and no longer available.
- The manufacturing technique is outdated.
- The skilled men are retired.
- The machines are no longer available.

These problems can be overcome technically. This means the parts has to be designed with modern materiel, design and manufacturing technique. The question is whether anyone can afford this.

All known Spare Stocks are under control. This will probably be the last resources.

As PROTEUS was designed without today's computer aid the safety margins on stress strength and cyclic life probably are large.

However the operational procedures changes and continues much longer than expected at the date of design. This could lead to previous never experienced problems.

Another foreseeable problem is the fact that very few of the personnel involved in the PROTEUS are still with ROLLS-ROYCE. The knowledge and expertise is slowly fading away. The workload on the few remaining staff members is steadily increasing.

THE FUTURE.

The Swedish Navy intends to run the PROTEUS into the year 2010.

Introduction of thorough engine condition monitoring together with all modifications has greatly improved the reliability of the engine. However this has to continue and be very carefully monitored to avoid severe damage to structural and other vital parts. Such parts are no longer available off the shelf nor can they be manufactured.

Next step will be to introduce continuous engine condition recording on board. The parameters would be: Overspeed, Overtemperature, Cyclic Life and Equivalent Running Hours.

Apart from Swedish Navy there are other operators that intend to run the PROTEUS to 2010 and even beyond.

In order to assist this ROLLS-ROYCE in 1996 started "PROTEUS Operators Seminar" for cooperation, exchange of information and to form a larger base for eventual Spare Parts production. This could also be an opening to the financial problems involved in the manufacture of spares. ROLLS-ROYCE also intends to head a Spare Parts Pool for exchange of spares between operators.

ACKNOWLEDGMENTS.

I wish to express my appreciation for encouragement in preparation of this paper to:

Mr. Jan-Erik Gustavsson Defense Materials Administration, Stockholm,
Mr. Lars-Göran Widmark, Volvo Aero Support, Arboga and
Mr. Lennart Ottosson, Teknikinformation MIU, Karlskrona.

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