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Chunnel

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Chapter 33

CHALLENGES, SOLUTIONS, AND REALITY IN TBMS

FOR THE ENGLISH CHANNEL TUNNELS

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INTRODUCTION

An English Channel Tunnel has been a dream for over 100 years. There are many records of concepts for making these tunnels and predictions of the resulting benefits of having them. Arguments against them have been equally numerous and have succeeded in preventing efforts going beyond a very minor stage.

During the 1980's the basis for the economic predictions of the costs and benefits of making and having these tunnels has become accepted to the extent that this huge undertaking is now well underway. The economic, technical, and political factors have now evolved to the point where it is generally accepted that the dream can come true. Resources and ideas are now being combined to make the Channel Tunnel a reality.

Many people around the world have worked to design and build tunneling equipment over the last 25 years. Through their efforts machine technology has advanced and overcome many of the difficulties of cutting and removing rock and soil from beneath the surface. Advancements in cutters, muck handling, ground support, shielding, ventilation, grouting, lining and machine control have been made.

Other people have operated these machines and have completed numerous impressive projects. They have learned much about machine performance and what can be expected in different applications.

This evolution and demonstration of technology is a key element in the transformation of a dream from being perceived as wild to being perceived as achievable.

B. ROBBINS COMPANY INVOLVEMENT IN THE CHANNEL PROJECT

The Robbins Company has been involved in some way in all of the recent attempts to complete the Channel tunnels. A machine was designed and manufactured for the French side in 1974. This machine was assembled but never put into operation. During 1987, The Robbins company was involved in the design and manufacture of 5 tunneling systems which will be used on both seaward portions of the Channel tunnels.

Detailed specifications and photos of the TBMs and systems are provided in the Appendix. The following figure defines the manufacturers cooperating in these efforts.

	1974 Project	1987 Project	
	Service Tunnel	Service Tunnel	Running Tunnels
Seaward British	Priestley	Howden	(2) Robbins Markham (R-2,R-3)
Seaward French	Robbins (-162 TBM)	(T-1) Robbins Komatsu	(T-2,T-3) (2) Robbins Kawasaki

FIGURE 1

MANUFACTURERS COOPERATING ON CHANNEL PROJECTS

There were major differences in these projects. These differences were brought about by changes and differences in the technological, contractual, economic, competitive, political and geological environments. Major differences existed in the requirements even between the two sides of the current project. These requirements are listed and compared in the next section.

C. AN IDENTIFICATION OF PROJECT REQUIREMENTS AND A COMPARISON OF THE TBM FEATURES

The undersea portion of the Channel tunnels is 37 km in length. One 5.8 M diameter tunnel and two 8.8 M diameter tunnels are being bored from each side. These tunnels are located entirely in chalk-marl.

British Side Tunnel Boring Machines

The British tunnels are located in homogeneous rock which is self-supporting, impervious to water and excellent for boring. Little water was expected.

These conditions determined the requirements and matching machine features which are shown in Figure 2. Normal boring conditions were expected to be near ideal. No difficult rock or water inflow conditions were expected. However, machine features were included to provide for emergency occurrence of blocky ground or high water inflows.

The -241 TBM is to begin boring during late January, 1989. The -242 TBM will start several weeks later. These machines are primarily designed for rapid advance. The double shield arrangement allows the tunnel to be bored while setting segments but allows the security of a shield if broken rock is encountered. The segments are designed for quick assembly as they are not bolted but expanded immediately against the tunnel wall.

Several design features are incorporated for emergency inflow of water. These include seals within the shield structure, an exterior expandable seal, a retractable conveyor with sealable opening, and expandable tail shutters which occupy the area of the normal tail shield and seal to the erected lining.

The thrust system, gripper system, and TBM structure are designed to withstand the loads that would result from sudden pressurization of the tunnel. Structural analysis was done using the finite element method and design considerations included stress, deflection and buckling.

French Side Tunnel Boring Machines

The rock on the French side is also chalk marl. However, the condition of the rock is broken and fissured for the first 2 kilometers. The fissures are filled with clay and water and are fed by the Atlantic Ocean. Water pressure was expected to be as high as 10 BAR and virtually unlimited in quantity. The 15 kilometers of rock beyond was expected to be relatively dry and ideal for boring.

These mixed conditions determined the features required in the machines and the type of tunnel lining. That high advance rates were required goes without saying. The mix of existing and new technologies that had to be combined was unusual. The resources of design, knowledge, experience, products and manufacturing capability did not exist in a single company. Resources from the USA, Japan, and Europe were combined to meet the delivery, performance, and content requirements demanded by the projects.

The French seaside service and running tunnel machines and systems are similar and are designed to operate under high water pressure or relatively dry conditions.

Figure 2 lists the requirements for the British and French seaside tunnels and also the individual TBM features. This table contrasts the difference in requirements and resulting TBM design features. Direct comparison of the French machine of 1974 and current machines can also be made.

The next section describes in more detail the features of the -235 TBM. The last section includes an update of performance to mid-January 1989. The specification sheets of all machines can be found in the Appendix.

FIGURE 2

Tunnel Conditions and Matching TBM Features

Requirements	TBM - 241/242 (1987)	TBM - 162 (1974)	TBM - 243/244 (1987)	TBM - 235 (1987)	Requirements
Seaward British	Robbins-Markham Double Shield 8.36 M Dia.	Robbins Double Shield 5.0 M Dia.	Kawasaki-Robbins Extendable CHD 8.8 M Dia.	Robbins-Komatsu Extendable CHD 5.6 M Dia.	Seaward French
Performance High Advance Rates	- High Power - Electric Dr. - Double Shld.	- High Power - Electric Dr. - Double Shld.	- High Power - Electric Dr. - Extend. CHD	- High Power - Electric Dr. - Extend. CHD	Performance High Advance Rates
Muck Removal Dry/Wet	Belt Conveyor	Belt Conveyor	Single Auger w/chain conveyor Single Auger w/double piston discharger	Double Auger Double Auger	Muck Removal Dry/Wet Mostly Water
Lining Expanded precast concrete (placed on wall/loose) (5 + key) Also periodic cast-iron	Single Arm Erector - no tail shield	Single Arm Erector - no tail shield	2 - Single Arm Erectors - in tail shield	2 - Single Arm Erectors - in tail shield	Lining Precast concrete (backfilled) (5 + key bolted) Also periodic bolted cast iron
Rock Conditions Continuity Homogeneous Blocky	Flat/Grilled Cutterhead 2 Speeds Shlded	Flat "Melbourne" Type Cutterhead Shielded	Flat/Grilled Cutterhead 2 Speeds Shlded	Flat/Grilled Cutterhead 2 Speeds Shlded	Rock Conditions Continuity Homogeneous Stratified Broken
Rock Conditions (Cont'd) Hardness Soft Medium	Drag Bits Disc Cutters	Drag Bits Disc Cutters	Drag Bits Disc Cutters	Drag Bits Disc Cutters	Rock Conditions (Cont'd) Hardness Soft Medium
Water Conditions Normal Low Volume No Pressure Emergency High Volume & Pressure	Invert Pumps - exterior shield seal - internal seals - conveyor opening gate - sealing tail shutters	Invert Pumps Pumps	Shield Tail/ Lining, seals, shield articu- lation seals, double auger Pumps	Shield Tail/ Lining, seals, shield articu- lation seals, piston discharger Pumps	Water Conditions Normal (and Worst) High Pressure (10 Bar) High Volume (but controlled) Emergency Machine System Leakage
Ground Treatment	Probe/Grout Drills	Probe/Grout Drills	Probe/Grout Drills	Probe/Grout Drills	Ground Treatment

D. DETAILS OF THE COMBINATION OF SPECIAL FEATURES REQUIRED TO SATISFY THE SPECIFIED OPERATION REQUIREMENTS FOR THE -235 (T-1) TBM

The Robbins-Komatsu TBM -235 is a shielded, rotary head machine which sets bolted precast segments. The machine can bore under dry conditions while setting segments. It can also bore under water pressure up to 10 BAR. Under pressure conditions the boring and segment setting are done separately. The machine includes a large diameter auger which discharges through either a gate under zero pressure conditions or through a double piston discharge pump when water is present and under pressure.

The auger reduces the water content of wet muck so that it can be handled with flight and belt conveyors and removed from the tunnel in muck cars. When the piston discharge pump is operating it serves as a pressure lock as the muck is moved from high to low pressure.

The specification sheet for this TBM is in the Appendix. This sheet lists the special rock boring and soft ground features of the machine.

Special New Designs, Design Evolutions, and Developments

Many of the new or special features of the -235 TBM required that new designs be developed or that existing designs be improved. Several of these required testing and retesting to confirm their capabilities to meet the requirements.

The requirements of particular importance were:

1. All seals had to meet certain leakage rates at 10 BAR pressures. Normal operational pressure levels had previously been 4 to 5 BARS.
2. The cutterhead, auger, and piston discharger had to be able to handle blocks of a certain size and also not get plugged by the chalk which gets very sticky when wet.
3. High capacity auger and piston discharger to meet high advance rates.
4. Thorough analysis to prevent stress or buckling failure of the machine structure and the tail shield particularly under high water pressure.
5. Designing and manufacturing corrosion resistance into the machine parts, in particular the tail shield.

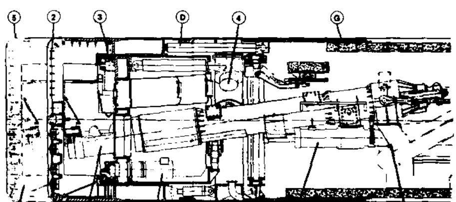
The scope and importance of the project presented challenges to people in all departments of our company during each phase of the effort to conceptualize, sell, design, manufacture, assemble, and operate the machines. The knowledge, skill, ability to communicate, and, last but not least, patient perseverance of individuals was often put to the test. The difficult requirements and competitive environment made even more difficult the need to understand and satisfy requirements, accurately define the supply scope, its cost and delivery schedule and then to control the design and manufacture to the predicted budget and schedule.

These TBM projects serviced as important exercises which have not only led to the development of machines with new combinations of tunneling technology but also improved certain individual, corporate, and managerial skills of the companies and people involved.

Model 1810-235

Rock Boring Features:

1. A cutterhead equipped with disc cutters. Rocker type drag picks can be installed in place of the discs in the same cutter housings.
2. Grill bars on the face and at the periphery of the cutterhead prevent ingestion of caving blocks.
3. High-capacity main bearing permits boring at high thrust and penetration rates.
4. Grippers provide thrust reaction during boring so segments can be placed while the shield jacks are retracted.
5. Extensible telescoping cutterhead provides for boring advance during segment placing.



Soft Ground Features:

A. Two-way buckets and cutters allow cutterhead rotation in both directions to counteract the tendency for the machine to roll as it reacts to cutterhead torque.
B. A complete shield with a pressure bulkhead.
C. An articulation joint, having seals to withstand 10 bar pressure, facilitates steering.
D. High-thrust shield jacks provide the cutting force, the thrust to overcome shield friction in squeezing conditions, and counteract the 10 bar fluid pressure against the front of the shield when boring in the closed mode.
E. High torque bi-directional drive with clutches provides sufficient torque for high penetration rates in both hard and soft conditions.
F. Shield tail seals of the greased wire-brush type in four rows.
G. Continuous extruded backfill grout system pumps grout in the cavity between the segments and the rock as it is exposed by the forward progress of the shield.
H. A screw conveyor removes muck from the cutterhead cavity to the rear part of the shield. This screw can be closed and sealed against 10 bar pressure either at the front or at the rear.
I. A twin piston discharger lowers the muck and water from the high pressure of the screw conveyor to the atmospheric pressure in the tunnel, where it can be removed in rail muck cars.
J. An alternative slurry system carries muck and water from the piston discharger through a crusher and piping to the tunnel portal or disposal site.

E. SUMMARY OF -235 (T-1) PERFORMANCE TO JANUARY 15, 1989

The -235 TBM was shipped from Portland, Oregon at the end of December, 1987. It began boring at Sangatte, France about February 26, 1988. Figure 5 and 6 show the monthly and total advance rates to January 15, 1989. Also listed are comments on milestones and "period" maximum advances.

From the perspective of the time of writing the last 10 weeks have been encouraging. During the presentation in June, I will update the graphs to the end of May and hopefully further improvements will have been made. The first 17 days of January yielded 217 meters. This advance rate promises a 400 meter month.

Unfortunately, some of the technical, operational, and site efficiency problems still exist. The early problems also fit into these categories. Under the pressure which exists in the early weeks of start-up it is often difficult to determine precisely what or who is causing delays and how and when the change or improvement is going to be made. Communication, understanding, assumption of responsibility, and action are vital to resolve delays quickly. Review of the changes in the monthly advance rates indicates improvements by a factors of 2 or 3 several times during the first 10 months.

From the actual set of initial causes of delay it took 6 months to determine what they were, how to fix them, who was going to fix them, and for that group to fix them. The second set of problems only took 2 months and resulted in a much greater overall improvement.

Some of these problems were:

Cutterhead - High torque requirements due to grill bar/scraper configuration did not leave enough torque for sufficient cutter penetration. Removal of grill bars in blocky ground suspected to have led to screw conveyor damage. Later changes to grill bars significantly reduced torque and design penetrations were reached.

Screw Conveyor - Forward door of screw conveyor and screw flight damaged. The screw was rebuilt and reinstalled.

Segment Erector - Tight clearances and interferences led to delay, difficult control, and long learning time. Controls redesigned and operator efficiency improved.

Operational - Site management assumed too much responsibility for machine operational procedures before the true nature of problems and optimum system operational procedures were set.

Site Efficiency - Poor availability of segments and trains for muck removal cause machine delays. Back-filling of the segments allowed segment set to distort. This in combination with drastic steering corrections led to erector, and gantry structure interferences with the lining.

1810-235 METERS BORED PER MONTH

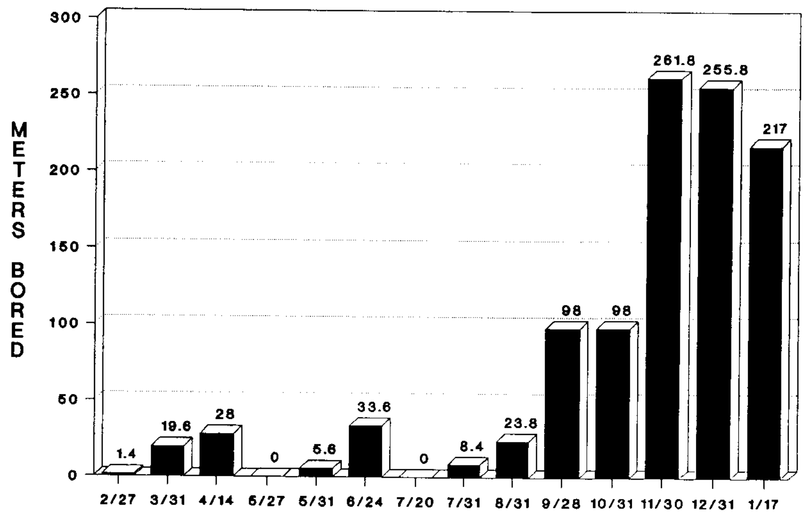
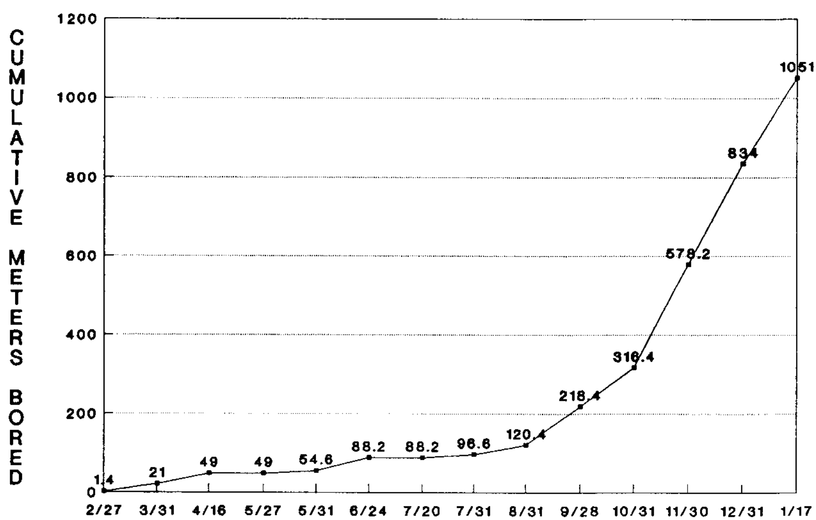


FIGURE 5

1810-235 CUMULATIVE METERS BORED



Best Day - (1/8/89) - 23.8 M

Best Week - (1/1 - 1/8/89) - 109.2 M

FIGURE 6

SUMMARY

Much of the tunneling development effort of the English Channel construction project which is now underway is included in the tunneling machines which are being used to construct the tunnels. Five of these machines are the result of cooperative efforts of several tunneling machine manufacturers. These companies are The Robbins Company, Komatsu, Markham and Kawasaki.

The different size, performance, geological, and lining requirements of the separate tunnels demanded different configurations and detail design features. Specific and often different technical approaches were brought to each machine by each manufacturer as determined by their particular strengths and the particular phase of the overall program.

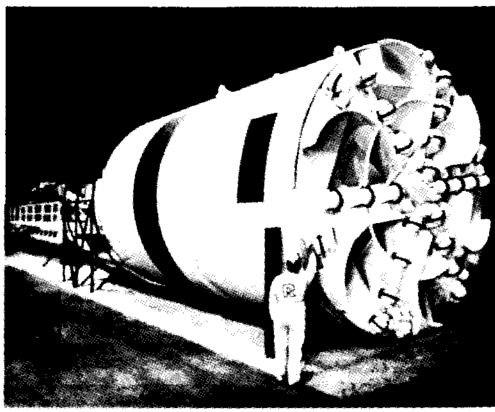
The machine owner/user was very involved in the determination of specifications and design of systems and structures. The negotiation procedures led to design evolution and restrictive, detailed contracts with severe penalties for delivery and TBM performance. The attractiveness of securing these contracts in combination with the need for local supply content led to a highly competitive and complicated sales environment. International linkages in the negotiation, design, manufacture and operation of these machines became necessary. These same requirements often added difficulties in the performance of the design and manufacturing work. Specific advantages were also derived.

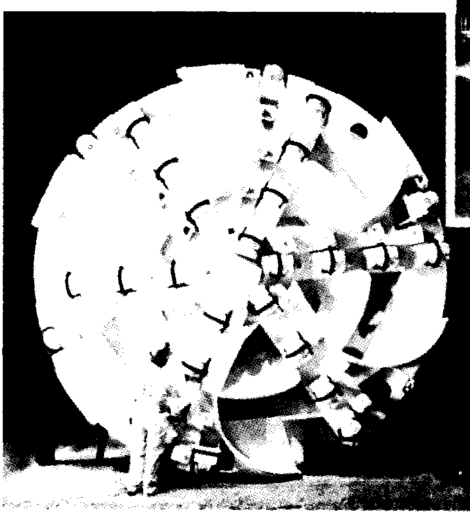
Review of the progress of the system shows expectations of reaching the required advance rates as improvements in efficiency and reliability are realized. The French seaward service tunnel machine had bored 1000 meters by January 10, 1989. In contrast, performance during the month of January, 1989 showed promise for reaching 400 meters.

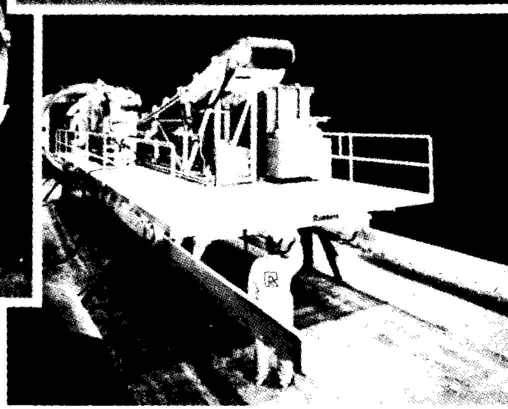
Completion of the Channel tunnels will be the result of the efforts of past and present individuals who dreamed and persevered to bring them into existence.

APPENDIX

model **165-162** | **Robbins Tunnel Machine**

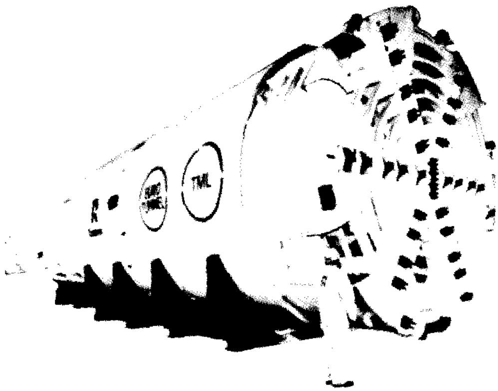


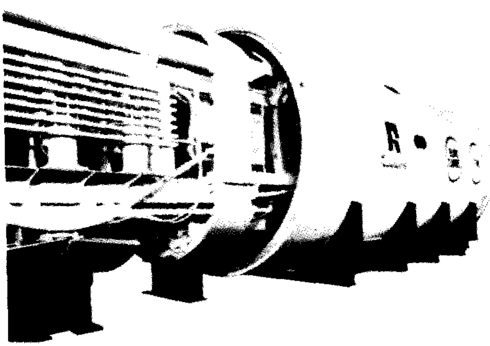




Project Information:

LOCATION	Channel Service Tunnel / Calais, France
MATERIAL	Chalk
COMPRESSION	Soft
SUPPORT	Cast Iron Liner Plates
TUNNEL LENGTH	16 miles (25.75 km)





Robbins Tunnel Machine

Model 1810-235

SHIELD MACHINE FOR HIGH WATER INFLOWS

Project Information:

LOCATION:
Channel Service Tunnel, France
ROCK DESCRIPTION:
Chalk Marl
UNCONFINED COMPRESSIVE STRENGTH:
70-350 kg/cm^2 (1-5 ksi)
TUNNEL LENGTH:
16.270 m (53.379 ft)

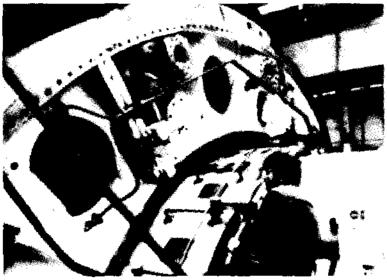
Machine Specifications:

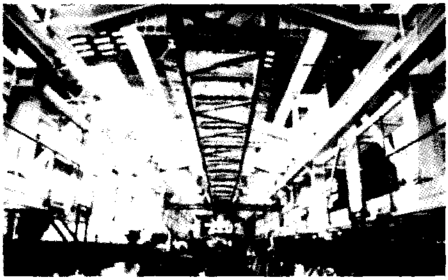
DIAMETER: 5,6 m (18 ft 4 in)
POWER: 880 kW (1180 hp)
THRUST:
Cutterhead (7 Cylinders):
1.200.00 kg (2,645,547 lbs)
Shield (20 Cylinders):
4.000.000 kg (8,818,490 lbs)
WEIGHT: 412 m tons (454 tons)
CUTTERS: 39-330 mm (13 in) discs
or 78 drag picks

Back-up Specifications:

DESCRIPTION: 17 gantries plus switch
WEIGHT: 647 m tons (713 tons)
LENGTH: 298 m (978 ft)

Specification





Specification for 2—Running Tunnel machines for Channel Tunnel UK Maritime Drivage.

Cut diameter	8.36m
Cutters alternatively	276 Rocking Picks 58 discs
Cutterhead torque	5.25×10^6 NM
Cutterhead speed	2.2 to 3.3 rpm
Cutterhead drive	12×110 kW Water cooled clutched electric motors
Number and stroke of advance rams	20×1500mm
Installed thrust to cutterhead	4220 tonne
Number and stroke of auxiliary thrust rams	16×2000mm
Installed thrust of auxiliary rams	470 tonne
No. of gripper shoes	4
Ground pressure from gripper (normal)	18.5 bar
No. of conveyors	3
Conveyor capacity	1500 tph

No. of segment erectors	2 upper & 2 lower
Segment delivery system	1 upper slat conveyor 1 lower conveyor
Fire fighting system	2 foam plugs 2 water curtains AFFF units Hand appliances
No. of back-up sledges	13
Electrical supply voltage	11,000/415v
Total installed power	2.3 mW
Emergency battery	900 ah
Water pumps	2 x 150 1/sec inrush 1 x 40 1/sec circulation 1 x 50 1/sec discharge
Ventilation system	300 m^3/min incoming 250 m^3/min extracted
Probe drills	2 DIAMEC 260
Machine weight (approx.)	1350 tonne
Machine length (overall)	250m

ROBBINS-KAWASAKI RUNNING TUNNEL MACHINES (T-2/T-3)

The contract for the design and construction of these machines was awarded in August 1987, approximately one year after the service tunnel machine (T1) was ordered. TML (Transmanche Link), the contractor for the French side of the tunnel, wanted a machine having the same conceptual design as T1, that is, operable in open and closed modes and utilizing an articulated shield for positive steering. The agreement between Robbins and Kawasaki was that the latter would be responsible for design and construction of the machines, while the former would provide design guidance based on the experience gained during the design phase of T1.

The cutterhead diameter is 8.78 meters, compared with 5.76 meters for T1.

While the basic operation of the machines are identical, there are detail differences in some major components. The cutterhead is a standard Kawasaki soft ground shield design, simultaneously using disc cutters and drag picks. The spoked design allows passage of muck through parallel sided slots.

Although both T1 and T2/T3 use a screw conveyor to remove the muck from the cutterhead, the means of accomplishing discharge under water pressure is entirely different. T1 uses a positive displacement piston pump that, through the use of valving, ensures that there is no direct connection at any time between the areas of high and low pressure. T2/T3 use a conveyor having two screws in series with a gap of controllable length between them. A plug of muck between the two screws serves to act as a pressure restrictioon and also to prevent the passage of free water. In addition the relative speeds of the two screws can be adjusted to provide control of the delivery rate. This conveyor is designated as the multi-control screw (MCS).

T1 uses controlled air pressure in the cutterhead main bearing and drive gear cavity to reduce the pressure differential at the sealing interface. T2/T3 is not employing this system but is relying on the seal to operate at the full 10 bar differential.

The larger size of the T2/T3 machines permitted the use of a drum mounted segment erector system, rather than the circumferential ring with cantilevered arms used on T1. As with T1, a vacuum system is used to hold the segments during installation.

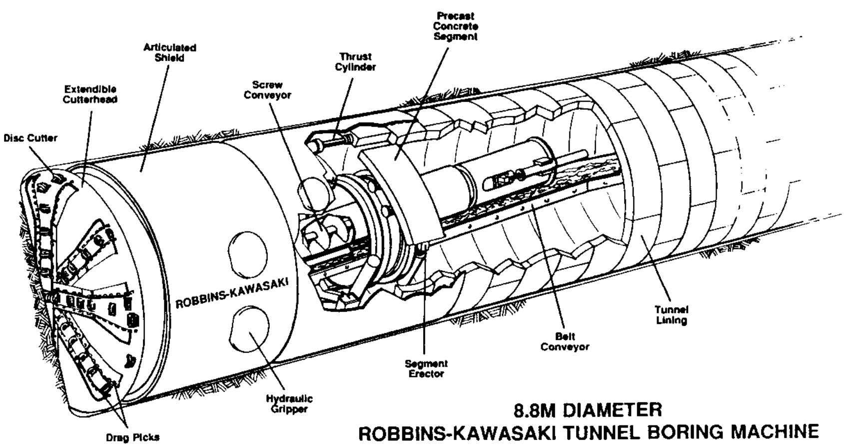
The backup system supporting the machine and tunneling operation is naturally larger than for the service tunnel. There is enough space to permit a double rail track inside the gantries, which allows shorter muck and delivery train cycle times. This, however, requires more complicated conveyor and unloading systems as both tracks must be served.

The T2 machine commenced operation in December 1988, on the northern rail tunnel. T3 is scheduled to enter service in March 1989.

Robbins-Kawasaki TBMs 291-241/242 Channel Running Tunnels, France

Specifications:

Bored Diameter:	8.8 meters
Number of Picks:	236
Number of Disc Cutters:	49 (381 mm ring)
Cutterhead Power:	12 x 180 kW (2160 kW)
Cutterhead Torques and Speeds:	650 ton-meters @ 3.0 rpm 1300 ton-meters @ 1.5 rpm
Cutterhead Thrust:	2000 metric tons
Cutterhead Stroke:	1650 mm
Shield Thrust:	11,500 metric tons
Gripper Thrust (Total) (Front Shield): (Rear Shield):	2200 metric tons 2000 metric tons
Instantaneous Penetration Rate:	12 cm/min (open mode) 9 cm/min (closed mode)
Advance Rate:	4.4 m/hr (open mode) 3.0 m/hr (closed mode)
Weight:	1000 metric tons



8.8M DIAMETER ROBBINS-KAWASAKI TUNNEL BORING MACHINE For Channel Tunnel Rail Tunnels