BELTCON 7

ATTEMPTS TO IMPROVE START-UP OF CONVEYORS FITTED WITH THE FLUID COUPLINGS OF A CONSTANT FILLING TYPE

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1. INTRODUCTION

Very long or highly powered conveyors are generally designed to utilise fairly complex control systems which govern start–up and/or stopping of such installations.

By doing so conveyor behaviour becomes predictable to the point that lower safety factors can be applied.

Due to various constraints smaller installations do not utilise such techniques and more often than not torque control during start–up is very basic at most.

One of the more popular devices used on the South African market is fluid coupling of constant filling type.

That long standing popularity has been recognised by the leading suppliers and significant effort has been made to improve operating characteristics of those couplings allowing their application to be used in longer and more powerful conveyors.

It is unfortunate that in some instances start–up performance is unsatisfactory and one of the remedies offered is replacement of the simpler torque controlling device (in this case fluid couplings of constant fill) with more complex and more expensive system.

Another fact is that bad start–up performance is compounded by inherent faults of the design.

The question then can be asked if an installation using fluid couplings of constant fill type can have its start–up performance improved without going into full re–design of the conveyor or replacement of major components.

The intention of the paper is to show that such possibilities exist and some of them are presented in more detail. It also indicates usefulness – of modern technology such as dynamic modelling as a diagnostic tool in such cases.

2. BRIEF TECHNICAL CONSIDERATIONS

Research done over the past two or three decades has given us clearer pictures of interdependence between a conveyor's physical parameters and its performance during transient stages of operation.

At the moment two basic concepts of acceleration/deceleration are used :

1. Torque based where motor torque becomes the main controllable parameter.

2. Velocity based whereby influencing certain drive qualities a specified pattern of speed increase is achieved.

In both instances the conveyor control system aims to achieve a pre–determined change of torque or velocity. Such an approach requires that the hardware used, either motor or torque controlling device, must be able to comply with the demands of the controlling unit. If this condition is fulfilled then a sophisticated start–up or stop can be achieved.

The fluid couplings of constant fill type do not fit into such a category.

The moment action is initiated i.e. the motor energised, any outside influence on torque generation is not possible. It is the coupling characteristic and interaction between components of the system that determine the conveyor behaviour.

Current practice tries to deal with that deficiency by development of sequencing procedure where electric motors are energised at prescribed time intervals.

It is meant to emulate torque ramp as advocated by Dr. H. Funke [University of Hanover] and as a result delay application of max. torque.

The process being of a discrete type is strongly influenced by the number of drives installed.

In theory an infinitely big number of drives would give results similar to that provided by scoop couplings for example. Such a system is of little practical interest as the sizes of drives would be infinitely small.

Practice does not come close to that model as in general one deals with max. 6 drives while the most common number is 3 or less.

In addition drives installed are selected with certain safety margins and are suited to satisfy a wider range of power demands.

The process of sequencing is done as a site commissioning exercise by trial and error, and very often due to time and operational restraints is not able to cover all possible conditions.

3. UTILISATION OF COMPUTER TECHNOLOGY

Computer technology becomes a common feature in controlling conveyor operation. In principle its application and operation is limited by our imagination and one can see installations where transient stages of operation (mainly starting) are governed by very sophisticated software.

In the case of the conveyors investigated in the paper purpose designed software may prove beneficial to the operation.

Performance of such software will obviously be limited by the restraints of the hardware but in some instances the time and money spent will be justified.

3.1 3.2 km Long Conveyor with a Booster Conveyor

A 3.2 km long conveyor was to be erected by linking together two existing installations.

To utilise available equipment to the full extent a concept of booster drive was applied. The new conveyor was fitted with 8 x 110 kW drives consisting of 4 pole motors, fixed fill fluid couplings of DFC type, gearbox and L.S. flange coupling.

Four of the drives were located at the head end to drive two drive pulleys while the remaining four were used to power the booster conveyor located ~ 1430 m from the head end.

Basic Conveyor Parameters

1.	Max. output	:	2200 t/h
2.	Belt speed	:	3,6 m/s
3.	Belt width	:	1200 mm
4.	Total length	:	3207 m
5.	Total lift	:	3 m

Motors were to be energised in a fixed sequence not dependant on load and power demand. The sequence used was as follows :

Time 0	:	Head end secondary drive No. 1
Time 4	:	Head end secondary drive No. 2
Time 8	:	Head end primary drive No. 1 and secondary booster conveyor drive No. 1
Time 12	:	Head end primary drive No. 2 and secondary booster conveyor drive No. 2
Time 16	:	Primary booster conveyor drive No. 1
Time 20	:	Primary booster conveyor drive No. 2

Start–up of the conveyor under full load is shown on Figure 1 and Figure 2 representing point close to the primary drive pulley at the head end and tail end of the booster drive respectively.

Both graphs are characterised by step like rise of tension and velocity. At the head end tension is stabilised for approx. 8 seconds followed by significant oscillation.

Average tension rise is 9542 N/S however localised gradients are in the region of 21091 to 24671 N/S.

Booster drive area (Figure 2) tension is oscillatory in character after peaking at 229,4 kN. Initial steps of the graphs reflect torque increase after energising of consecutive motors.

In addition tension in the area of the tensioning unit and in the front of the booster conveyor were allowed to drop significantly.

It has been recognised that within the existing restraints full control of the torque will not be achieved but possibly start–up behaviour could be improved by targeting the following aspects.

1. Interlink between conveyor power demand and start–up parameters.
2. Sequencing of the drives controlled by the PLC.
3. Limitation of total torque delivered to the system.
4. Prevention of unstable operation within the booster area.

The last point is of importance, during analysis of the conveyor it was found that the proposed start–up logic did not take care of some of the partial load cases, namely those where the booster conveyor area was not loaded to a significant degree.

As a result permanent slip between two belts could be registered at the stage when the forces introduced into the system exceeded the limiting frictional force between two belt surfaces.

Performance of the conveyor during a fully loaded start–up using modified control logic is shown on Figure 3 and Figure 4 (once again showing a point close to the primary drive pulley at the head end and tail end of the booster drive).

Rise of the tensions at both points is still of step–like character as no modification to the characteristics of motors and/or fluid couplings was attempted.

Average rise of tension at the head end is 4693 N/S with localised gradients of similar values as previously.

It is however interesting to note that graphs of velocities have changed their pattern. This specifically applies to the head end and to a smaller extent to the booster drive area.

The Phase of relatively constant tension is characterised by small oscillations at both locations and is significantly longer than the one on Figure 1.

It can be noted that as a result of dynamic control of the system only 6 drives are energised initially in a sequence while two remaining (1 at the head end and 1 at the booster conveyor) are brought into action very late during start–up. The fact is registered on the graphs as a small step on both lines of tension and velocity.

An additional important benefit can be seen in the smooth transition from acceleration to normal run phase.

The problem of the booster conveyor slip has been resolved to a larger extent, although not fully eliminated. One such instance is when the conveyor is started immediately after stopping. Increased oil level in the coupling's working chamber produces higher torques with all the detrimental consequences for a partially loaded booster conveyor.

4. UTILISATION OF THE VOLTAGE RAMP

Accepting shortfalls of the concept presented above, a different start–up control system has been analysed on a similar conveyor, also designed with a booster drive.

In this instance only 5 x 110 kW drives are installed with identical components. Three of the drives are fitted at the head end, two at the booster conveyor.

Basic Conveyor Data

1.	Max. output	:	1650
2.	Belt speed	:	2,72 m/s
3.	Belt width	:	1200 mm
4.	Total length	:	2382 m
5.	Total lift	:	9,4 m

Head end drives are energised in a fixed sequence as was described previously.

Booster conveyor drives come into action once a certain level of belt movement is reached.

In addition the motors are energised at a reduced voltage which is ramped up over an extended period of time.

Figure 5 and Figure 6 show the performance of the conveyor during a fully loaded start–up. Significant improvements can be seen both in the case of tensions and velocities. The step–like pattern of tension rise has disappeared.

This can be explained by the performance of the electric motor (Figure 7).

Within the first 4.5 seconds the motor accelerates up to its nominal rpm. As the torque generation of the coupling is a function of n^2 (n – motor rpm) the torque delivered to the drive pulley rises as slowly.

The fact can be noted on the graph of tension of Figure 5. Further on the torque curve is dominated by the natural curve of the fluid coupling. This pattern is repeated for each energised motor and results in a smooth transition between i and i + 1 motors in operation.

The concept in its presented form does not provide smooth start–up in the case of partial loads.

Figure 8 does not show any significant change of pattern at the head end, however the rise of speed is steeper and the oscillation of tension can be noted as a result.

A different picture is presented in Figure 9 showing the performance at the tail end of the booster conveyor. Clear signs of permanent slip between two belts can be seen between 9 and 12 seconds.

Performance of motors is exemplified by Figure 10. One can note that only a short portion of the coupling characteristic has been used. Initial stage of motor acceleration can be clearly seen.

The situation can be rectified by application of a dynamic system for the control of the booster drives as described in para. 3.

Further investigation into the voltage ramp or application of dynamic ramping possibly would improve conveyor start–up further.

5. APPLICATION OF FLY WHEELS

Over the past decade one has seen the return of the fly wheels in conveyor design. This has been done mainly by Conveyor Dynamics Inc. as part of philosophy of controlled stopping of long and/or high powered conveyors.

In such instances a fully controlled start–up was performed and the application of the fly wheels was of secondary interest.

It will be shown in the following paragraphs that a fly wheel may significantly improve conveyor performance in the absence of full torque control. Obviously it cannot be a cure for major design deficiencies however in some instances it may improve the situation to the extent that conveyor may perform in an acceptable way.

5.1 Brief Technical Considerations

If one looks at the acceleration of a conveyor (assuming rigid body model) the following formula applies :

$$a = \frac{A \bullet Mr \bullet D - Te \bullet D^2}{\Sigma m \bullet D + Jm} \qquad (1)$$

where

$A = 2 \bullet i \bullet \zeta$

i – gearbox ratio

ζ – average efficiency of the drive train

D – drive pulley diameter [m]

Te – effective tension [N]

Σm – total mass of the system excluding inertia of the drive train [kg]

Jm – total inertia of the drive train [kgm²]

If two different load conditions are denoted by 1 and 2 then :

$$\Delta a = \frac{a_1}{a_2} = \left[\frac{\Sigma m_2 \bullet D + 4 \bullet Jm}{\Sigma m_1 \bullet D + 4 \bullet Jm}\right] \qquad (2)$$

where

$$B^{-1} = \frac{A \bullet Mr_1 - Te_1 \bullet D}{A \bullet Mr_2 - Te_2 \bullet D}$$

then

$$Jm = \frac{D \bullet (\Delta a \bullet \Sigma m_1 - \Sigma m_2)}{4 \bullet (1 - \Delta a \bullet B)} \qquad (3)$$

Equation (3) must fulfill basic condition of $Jm > 0$ as the value includes inertia of drive pulley, gearbox, coupling, electric motor and fly wheel if required. From that two basic conditions can be derived :

a) $\Delta a > \frac{\Sigma m_2}{\Sigma m_1}$ and $\Delta a < B^{-1}$

or

b) $\Delta a < \frac{\Sigma m_2}{\Sigma m_1}$ and $\Delta a > B^{-1}$

Either a) or b) will be technically correct and will indicate the range of accelerations to be considered and lead to the initial selection of the value Jm. This in turn will allow selection of the fly wheel inertia.

One of the problems faced when torque is not controlled is the estimation of values Mr_1 and Mr_2.

If information is available average torques during start–up shall be used for condition 1 and condition 2.

Otherwise initial assumption of $\frac{Mr_1}{Mr_2} = 1$

could be a starting point for further investigations.

All above formulas will provide us with some information regarding sizes of the fly–wheels, average acceleration rates but very little can be gathered about possible dynamic response of the conveyor. Such information can be gathered on site or by application of modern design tools.

5.2 Conveyor behaviour Analysis

For the purpose of evaluation a dynamic model of a conveyor has been created. Basic conveyor data is specified below :

Basic Conveyor Data

1.	Total conveyor length	:	474 m
2.	Total conveyor lift	:	32 m
3.	Installed power	:	2 x 300 kW
4.	Max output	:	3500 t/h

The conveyor is characterised by significant differences in total mass between empty and fully loaded condition and also (which is an important difference) in power demand.

$$\frac{Te_1}{Te_2} = 12{,}4 \quad \text{and} \quad \frac{\Sigma m_1}{\Sigma m_2} = 4{,}7$$

1 – Full load 2 – Empty

The conveyor has been modelled with two drive pulleys each driven by a 300 kW motor. Complete drive unit consists of a fluid coupling of DFC type, gearbox and low speed coupling.

Energising of the motors has been done in a fixed sequence where at :

t = Os	secondary motor is energised
t = 2s	primary motor is energised

Inertia of the fly wheels considered were increased in steps as a function of the inertia of the motor i.e. 1 x Je; 2 x Je; 3 x Je etc.

Both empty (Figure 11 to Figure 15) and fully loaded (Figure 16 to Figure 20) start–up were considered.

All graphs mentioned above show change of tension and velocity at the point close to the primary drive pulley.

The following observations can be made.

1. Significant difference in total system mass and power demand manifests itself in distinctly different conveyor behaviour during acceleration (Figure 11 and Figure 16).

   Empty conveyor (head end) reaches almost full speed in 3 seconds against 9 seconds for the fully loaded case. Oscillations of tensions are significant.

2. Empty start–up is improved by the addition of fly wheels and their increase of inertia.

   Change of the velocity pattern can be noted already for fly wheels 1 x Je (Figure 12). However increase of the inertia beyond 3 x Je (Figure 14 and Figure 15) does not provide any substantial improvement.

3. Improvement in the tension pattern is not as rapid as for velocities. This can be pictured by the table below showing relationship between fly wheel inertia and max difference of tensions ΔF.

TABLE 1

FLY WHEEL INERTIA	ΔF [N]
0	146317
1 x Je	137439
2 x Je	103464
3 x Je	82929
4 x Je	71031

The table further suggests that there is certain limit of improvement which will not be exceeded irrespective of the fly wheel size.

Further analysis showed that min ΔF achieved would be not smaller than 65 kN and is reached rapidly with the fly wheels bigger than 4 x Je.

The most significant feature of the tension graphs is flattening of the curve over a significant portion of acceleration time.

4. Improvement of the start–up is also confirmed by the motor performance curves (Figure 21 and Figure 22).

5. Fully loaded start–up is affected by the fly wheels to smaller extent, however initial change of ΔF is of significance. In general it can be said that the fly wheels do rather minor smoothing out of the graphs of tensions and velocities. This can be explained by the change of ratio between the total mass of the system and equivalent masses of the fly wheels as well as a better match between system demand, power demand and torque generation by the drive units.

   Fly wheels bigger than 2 x Je produce practically insignificant improvements (Figure 18, Figure 19 and Figure 20).

   The following table indicates quality of change :

TABLE 2

FLY WHEEL INERTIA	ΔF [N]
0	202255
1 x Je	163915
2 x Je	159165
3 x Je	151431
4 x Je	143060

5.3 Practical Application

The analysis presented above confirmed the original objectives but also indicated several possible problems related to the application of the fly wheels. These have not been discussed here as they mainly relate to the proper conveyor design procedures but may be of importance when the fly wheel concept is applied to existing installations.

To verify some of the findings an existing 1,4 m overland conveyor has been analysed. The conveyor is known to behave violently during start–up with additional instabilities of the belt apparent at the lowest point of the conveyor profile (during empty start–up).

Power is delivered to the system by means of two drive units fitted with fluid couplings of constant fill type. Each drive unit is mounted on a separate drive pulley. Tensioning is by means of a gravity take–up.

Figures 23, 24, 25, 26 show the performance of the conveyor in the original state. Of interest are Figure 24 and 26 where a significant drop of tension can be noted. In fact tension levels are such that the belt no longer acts as a tensioned supporting member.

Taking into account the original analysis fly wheels were introduced into the system and the start–up simulated as for the original case.

Figures 27, 28, 29, 30 show the results.

Several things can be noted :

1. Pattern of tension and speed change has been improved over entire length of the conveyor.

2. Tension drop has not been prevented but restricted to much higher values (12,9 kN against 2,9 kN).

3. There is no sudden surge of tension and velocity after second motor is energised as it was the case originally (Figure 27 v Figure 23).

4. Care must be taken when selecting fly wheel size as there seems to be tendency of sudden drop of tension just beyond the secondary drive pulley after the primary motor had been energised. In some instances additional corrective action may be required.

6. CONCLUSIONS

Three concepts have been presented out of a much wider range of possible ways of improvement of start–up performance.

Each one of these presents the designer or the user with the means of controlling conveyor behaviour during acceleration. All of them can be used separately on their own or combined in one working system.

Application of computer technology provides benefits of control without major changes of conveyor components. End effects may be of limited quality specifically when torque characteristic of the drive are poor and the conveyor is characterised by inherent deficiencies.

On the other hand a fully dynamic control system can be created.

The voltage ramp as presented in the paper showed a significant change in the conveyor performance but possibly would benefit from the assistance of purpose designed software to achieve a dynamic system reacting to the changes of power demand, load condition etc.

The fly wheel concept is simple and reliable and may provide an answer for installations performing badly during start–up or stopping. The main advantage of this concept can be seen in its independence from power supply and outside control systems.

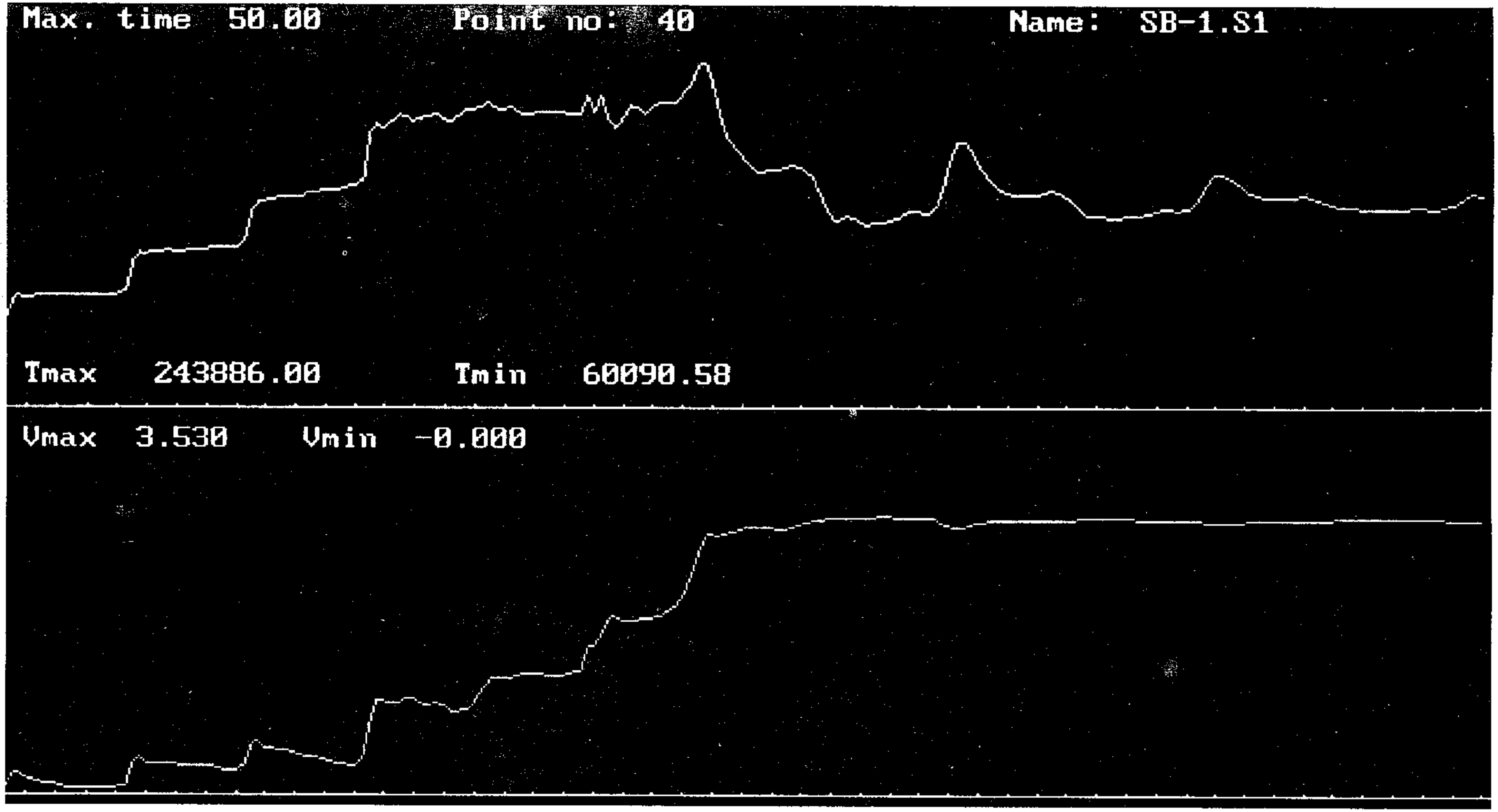
In all the above cases selection of the correct parameters of the control system is vital to the success of the exercise.

M. OTREBSKI
9 August 1993

FIGURE 1

a

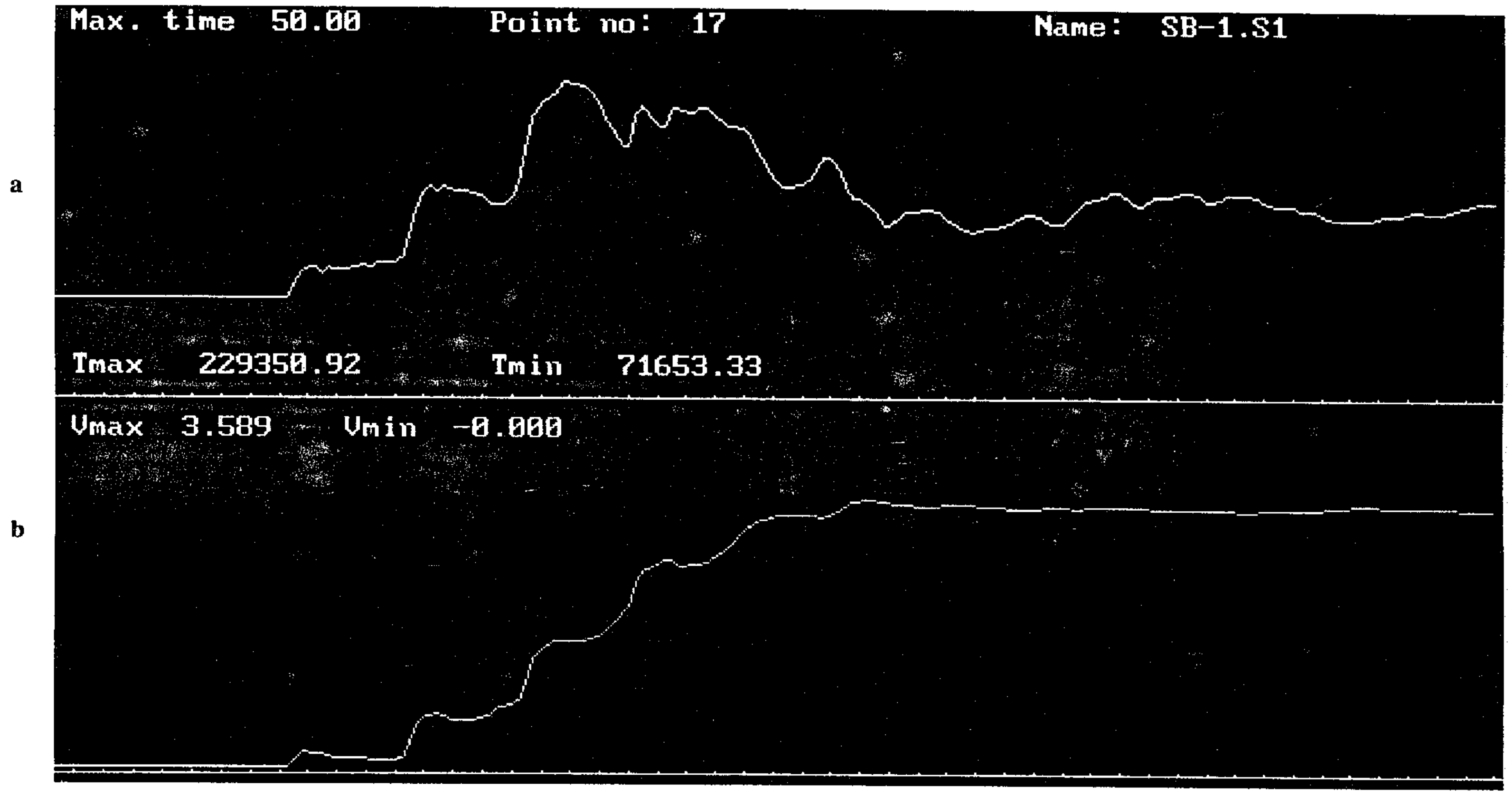
b



Fully loaded start–up. Point close to the primary drive pulley at the head end (original concept)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 2



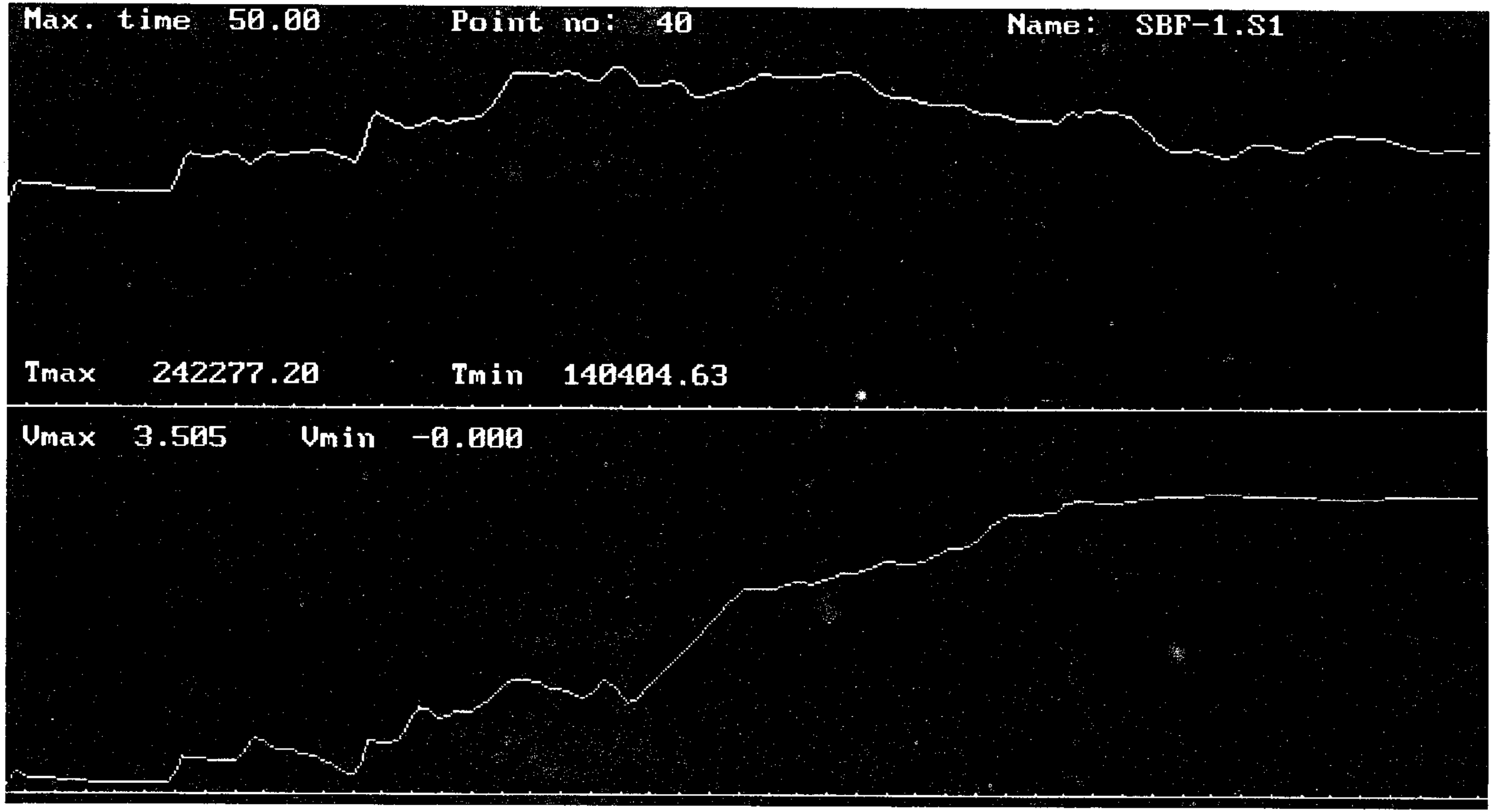
Fully loaded start–up. Point close to the tail end of the booster conveyor (original concept)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 3

a

b



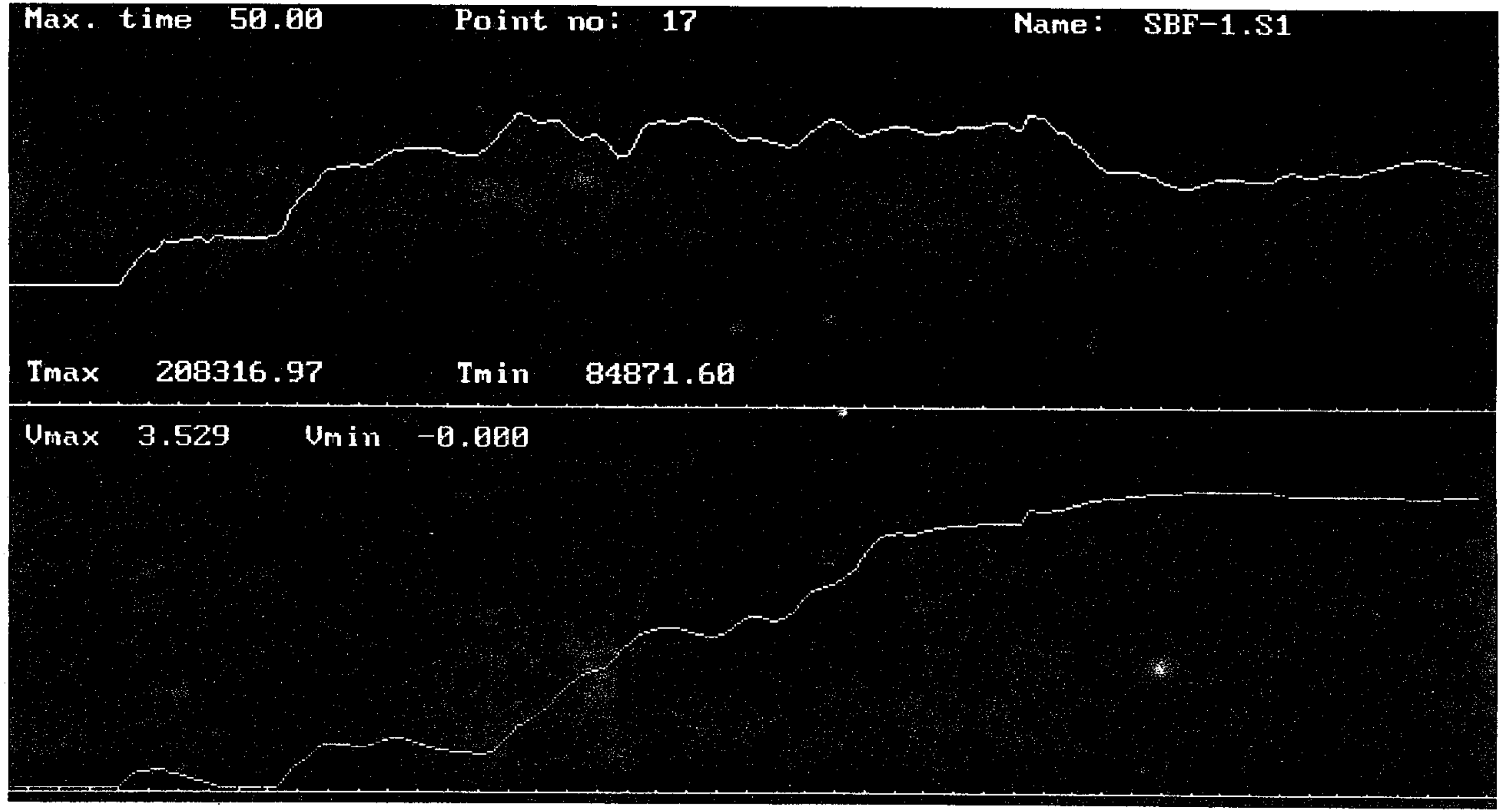
Fully loaded start–up. Point close to the primary drive pulley at the head end (original concept)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 4

a

b



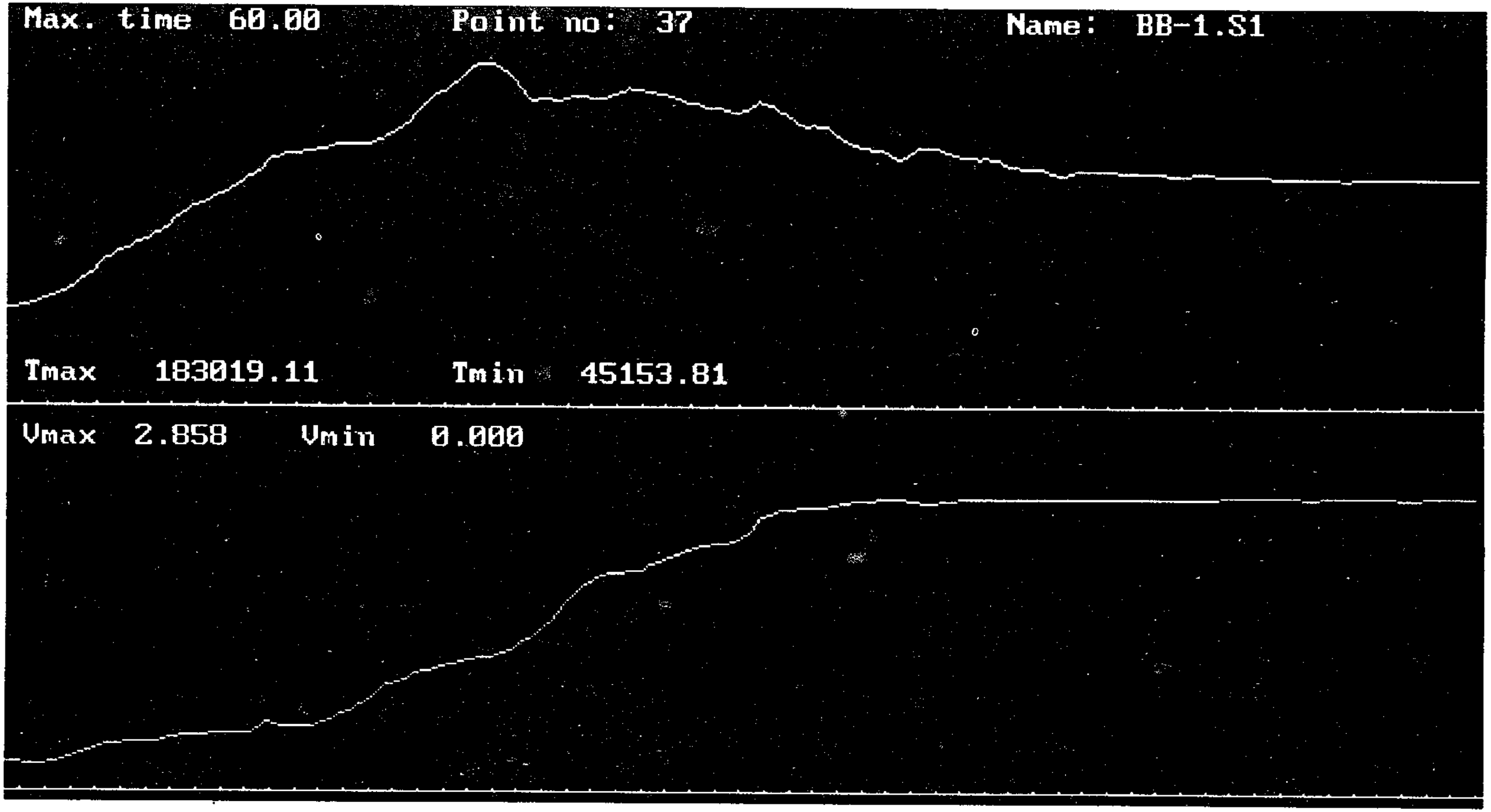
Fully loaded start–up. Point close to the tail end of the booster conveyor (revised concept)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 5

a

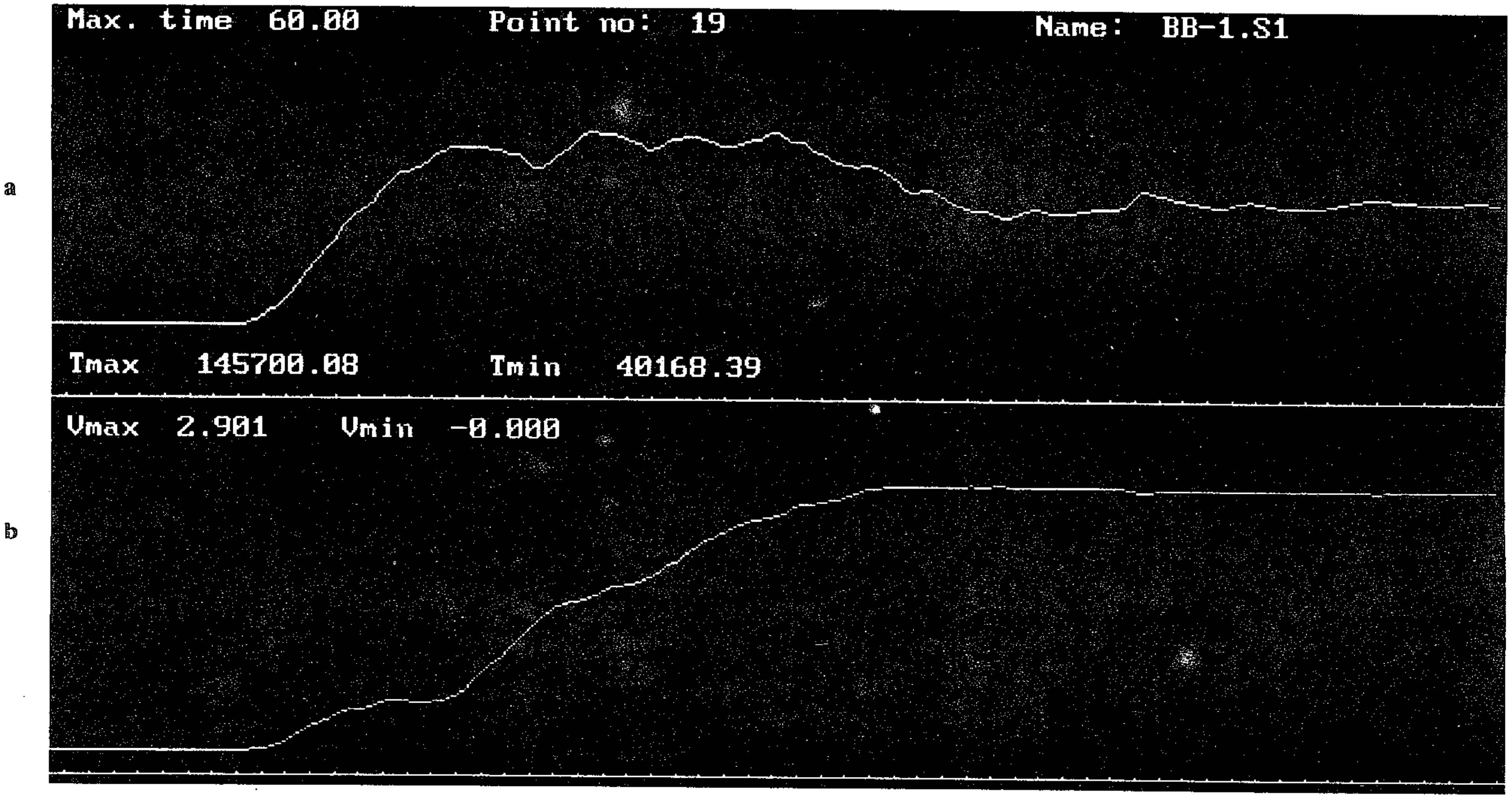
b



Fully loaded start–up. Point close to the primary drive pulley at the head end (voltage ramp)

a. Graph of tension [N]
b. Graph of velocity [m/s]

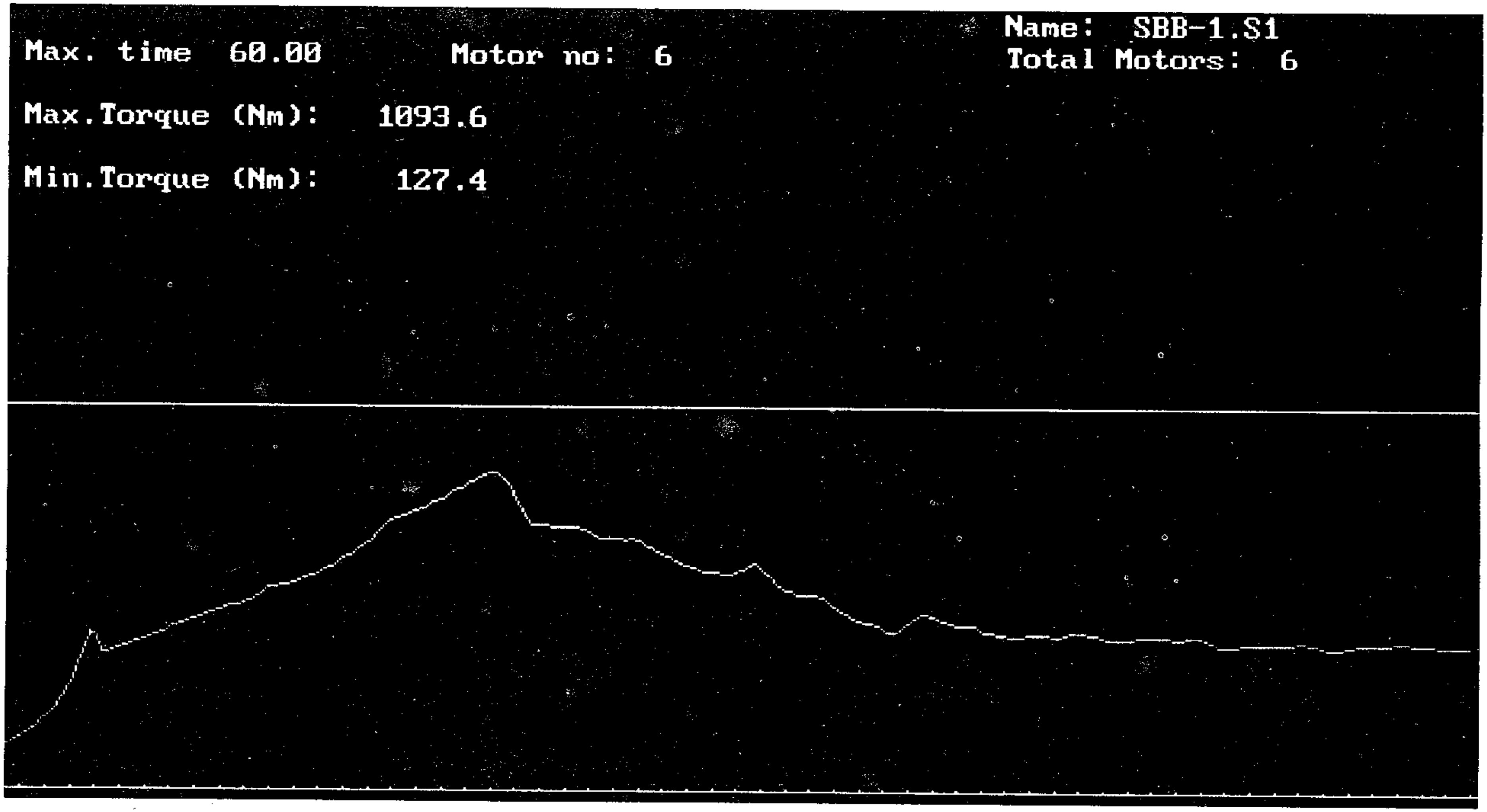
FIGURE 6



Fully loaded start–up. Point close to the tail end of the booster conveyor (voltage ramp)

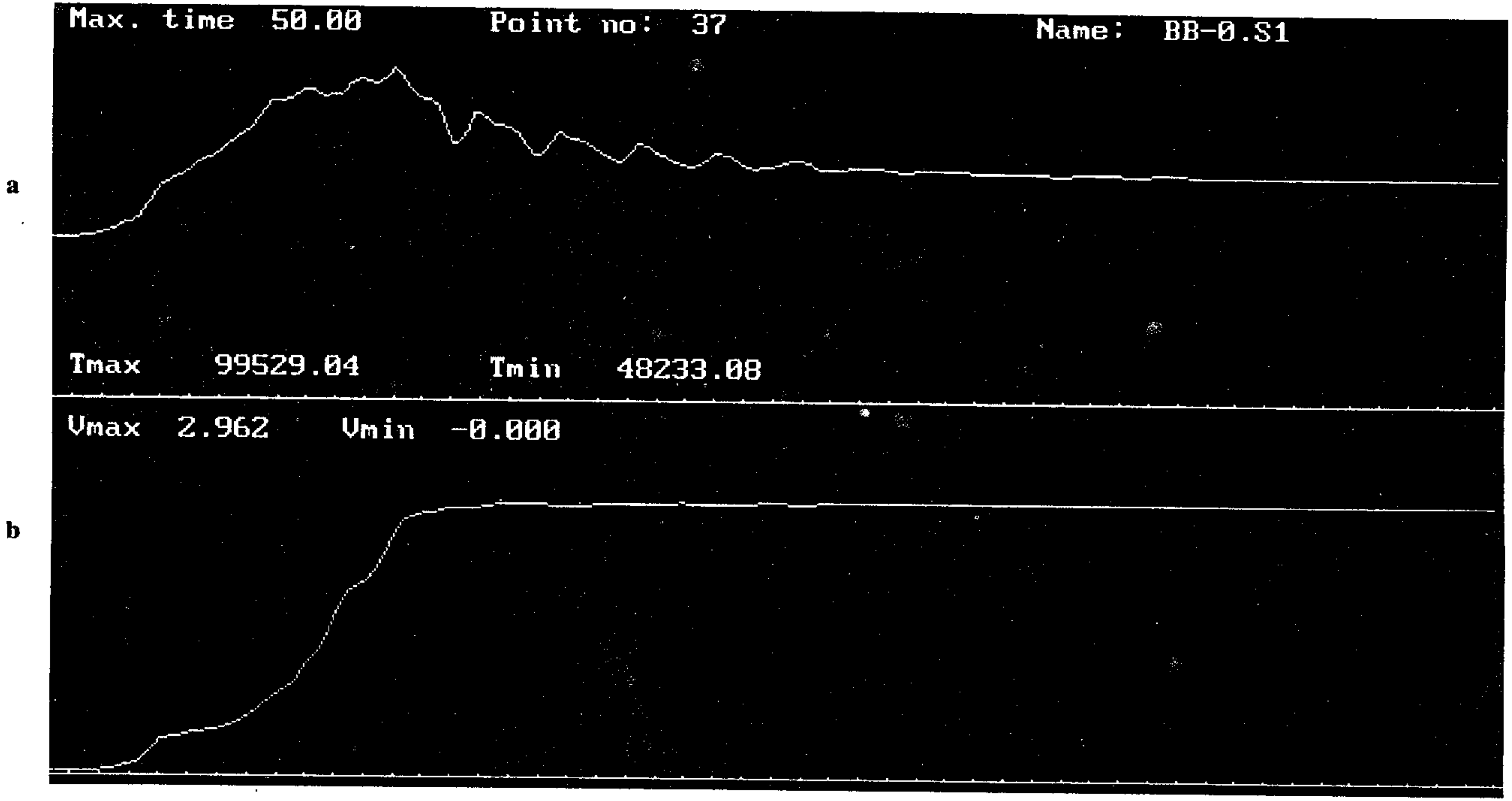
a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 7



Motor torque [Nm] during fully loaded start–up (voltage ramp)

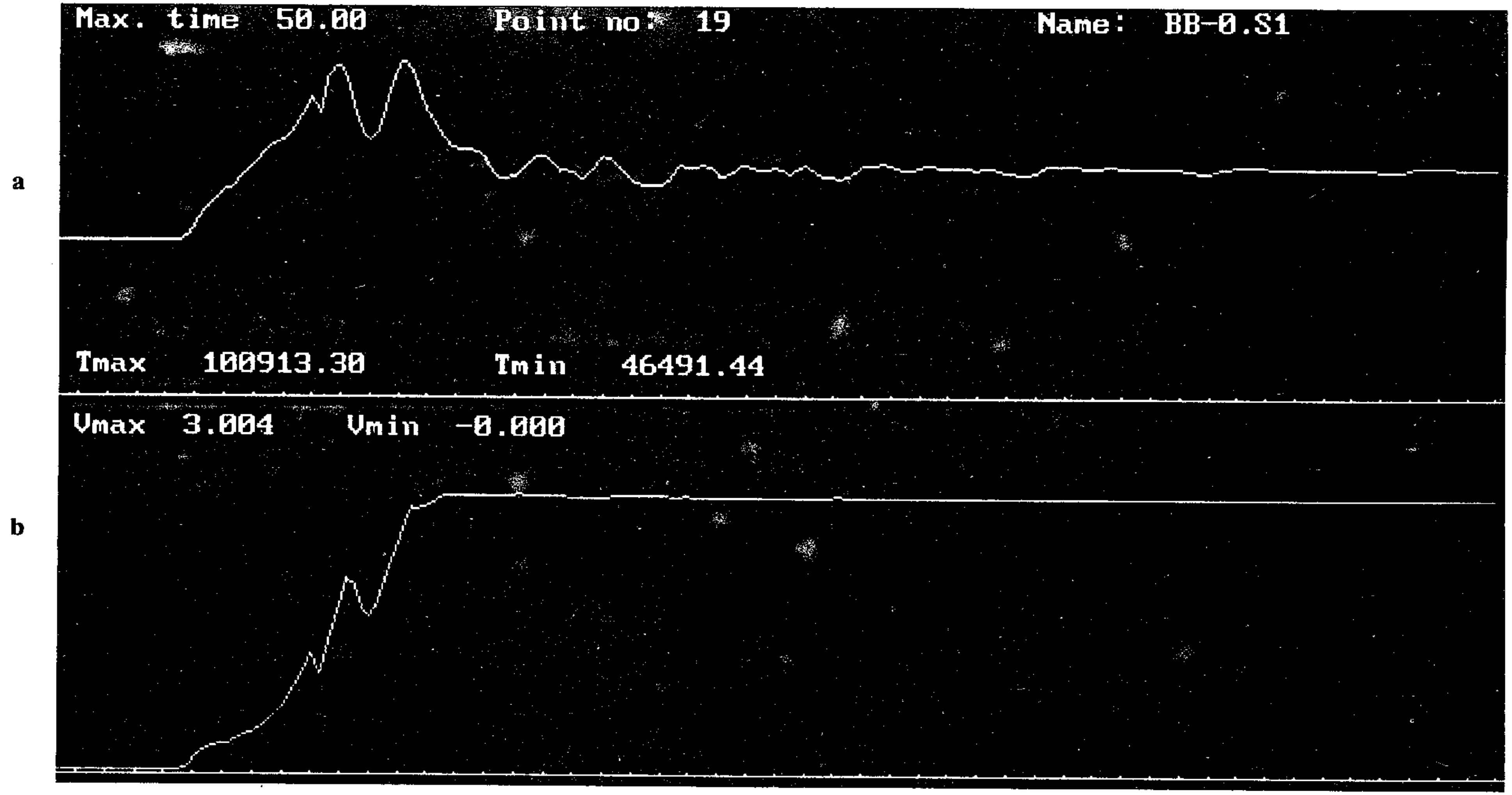
FIGURE 8



Empty start–up. Point close to the primary drive pulley at the head end (voltage ramp)

a. Graph of tension [N]
b. Graph of velocity [m/s]

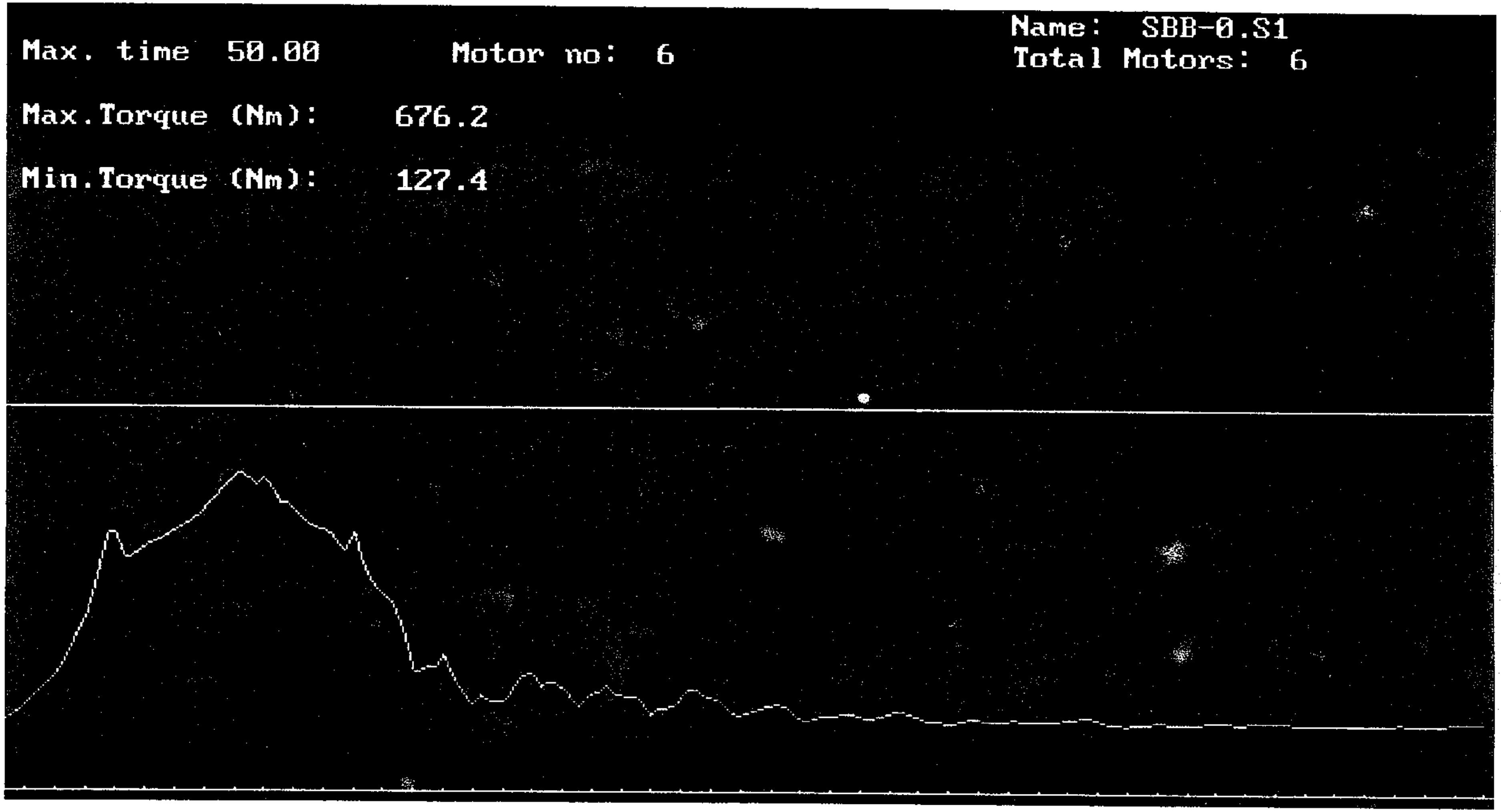
FIGURE 9



Empty start–up. Point close to the tail end of the booster conveyor (voltage ramp)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 10

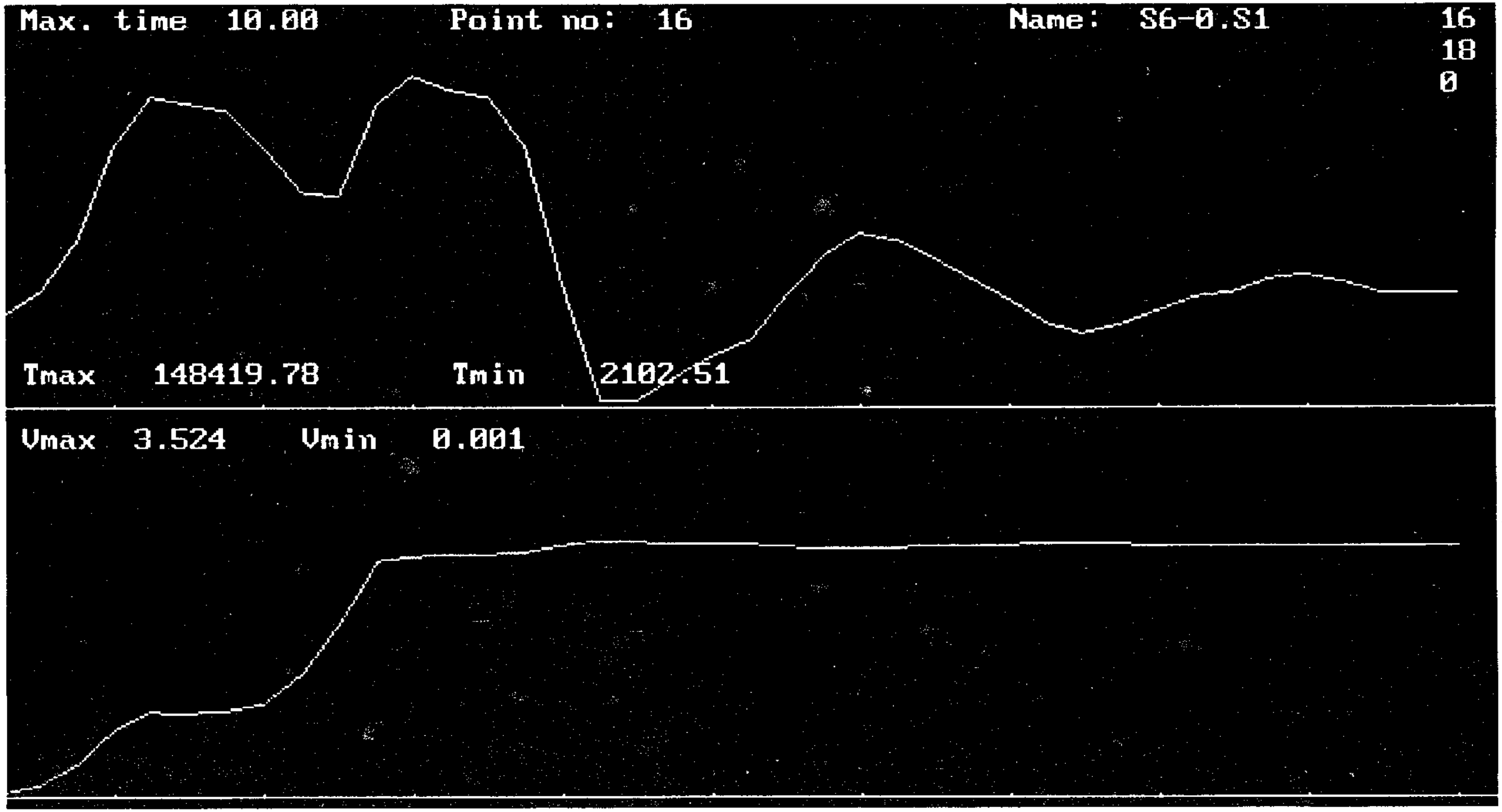


Motor torque [Nm] during empty start–up (voltage ramp)

FIGURE 11

a

b



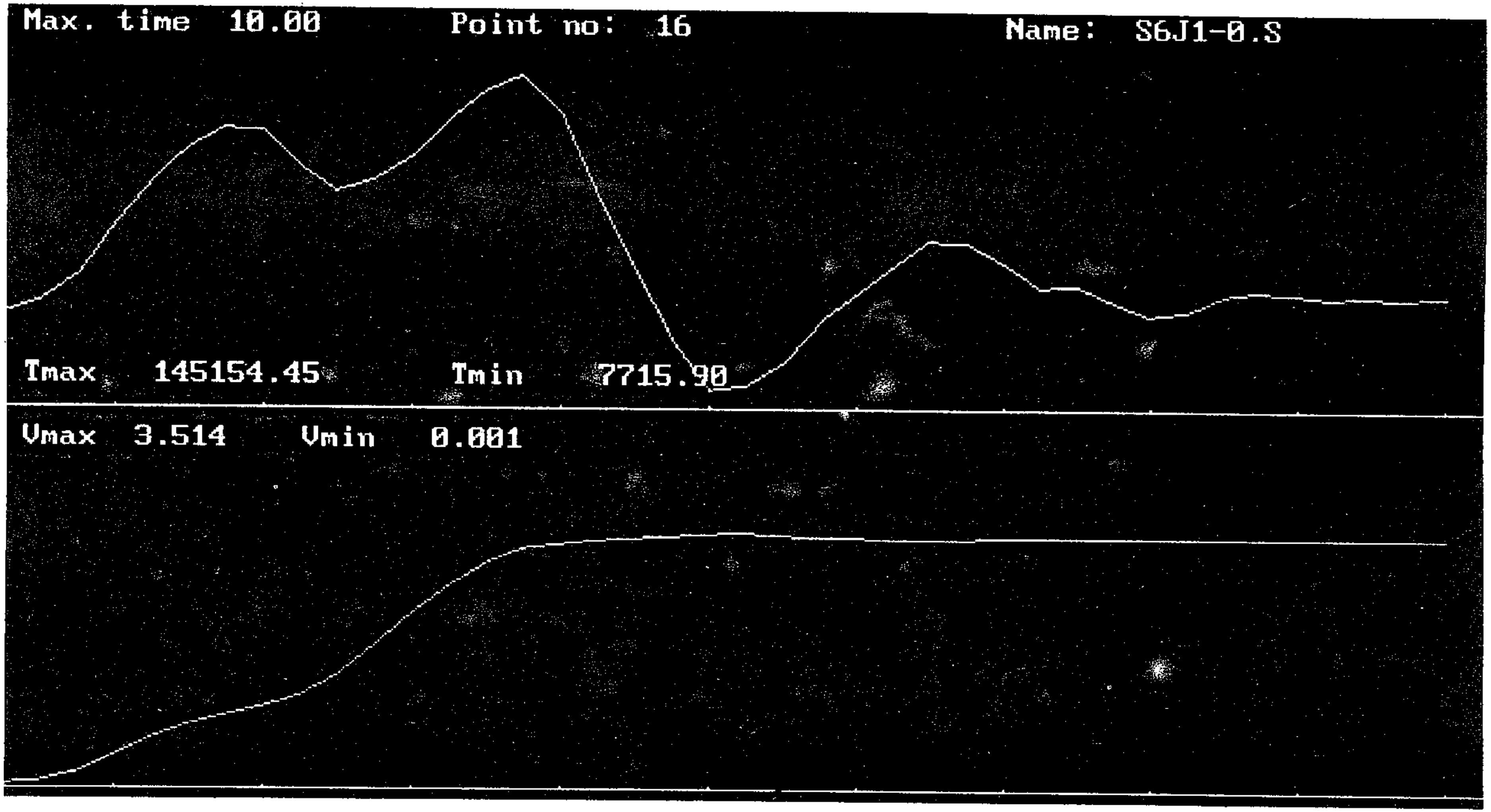
Empty start–up, no fly wheels. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 12

a

b



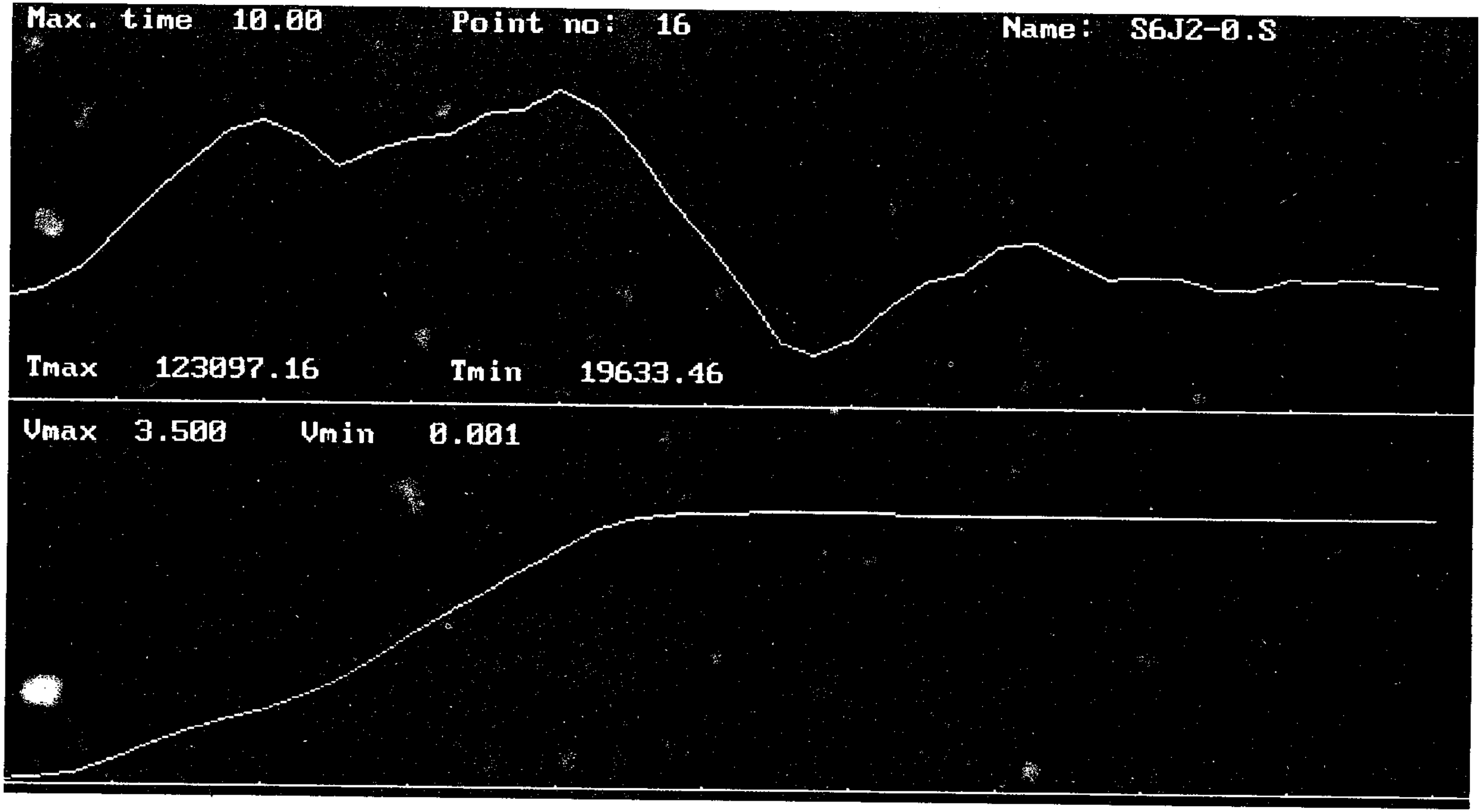
Empty start–up, fly wheels 1 x 1e. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 13

a

b



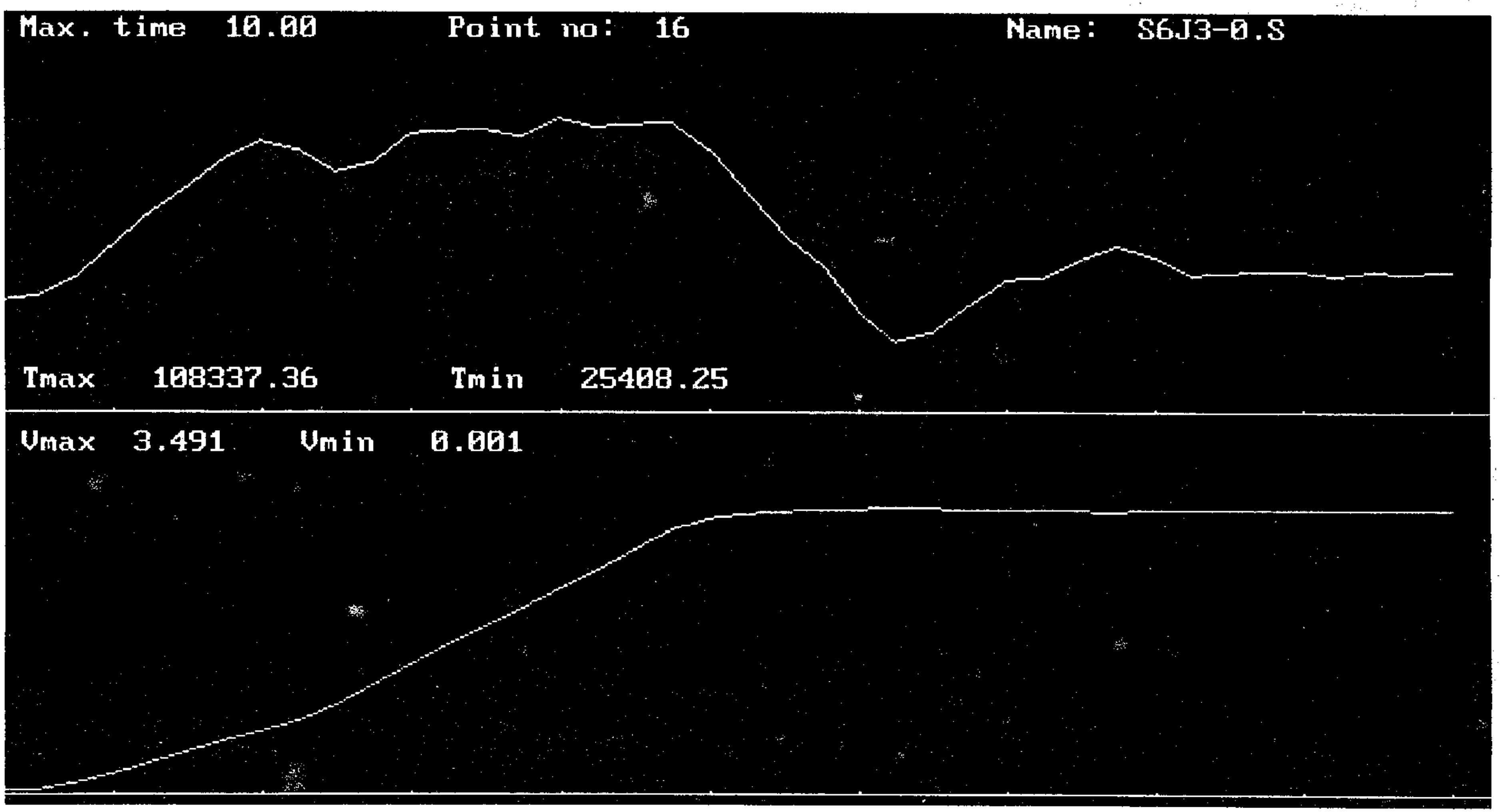
Empty start–up, fly wheels 2 x Te. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 14

a

b



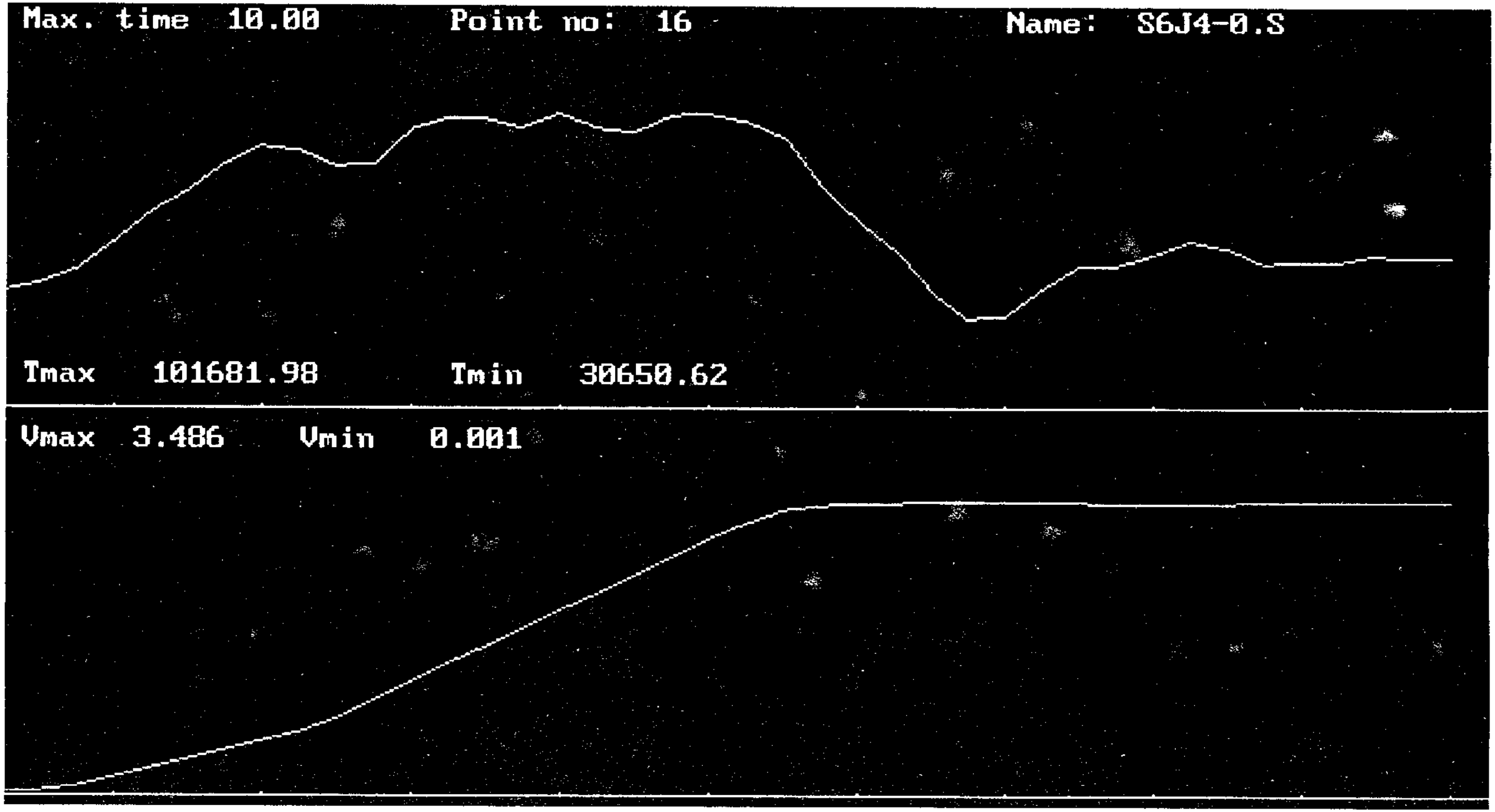
Empty start–up, fly wheels 3 x 1e. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 15

a

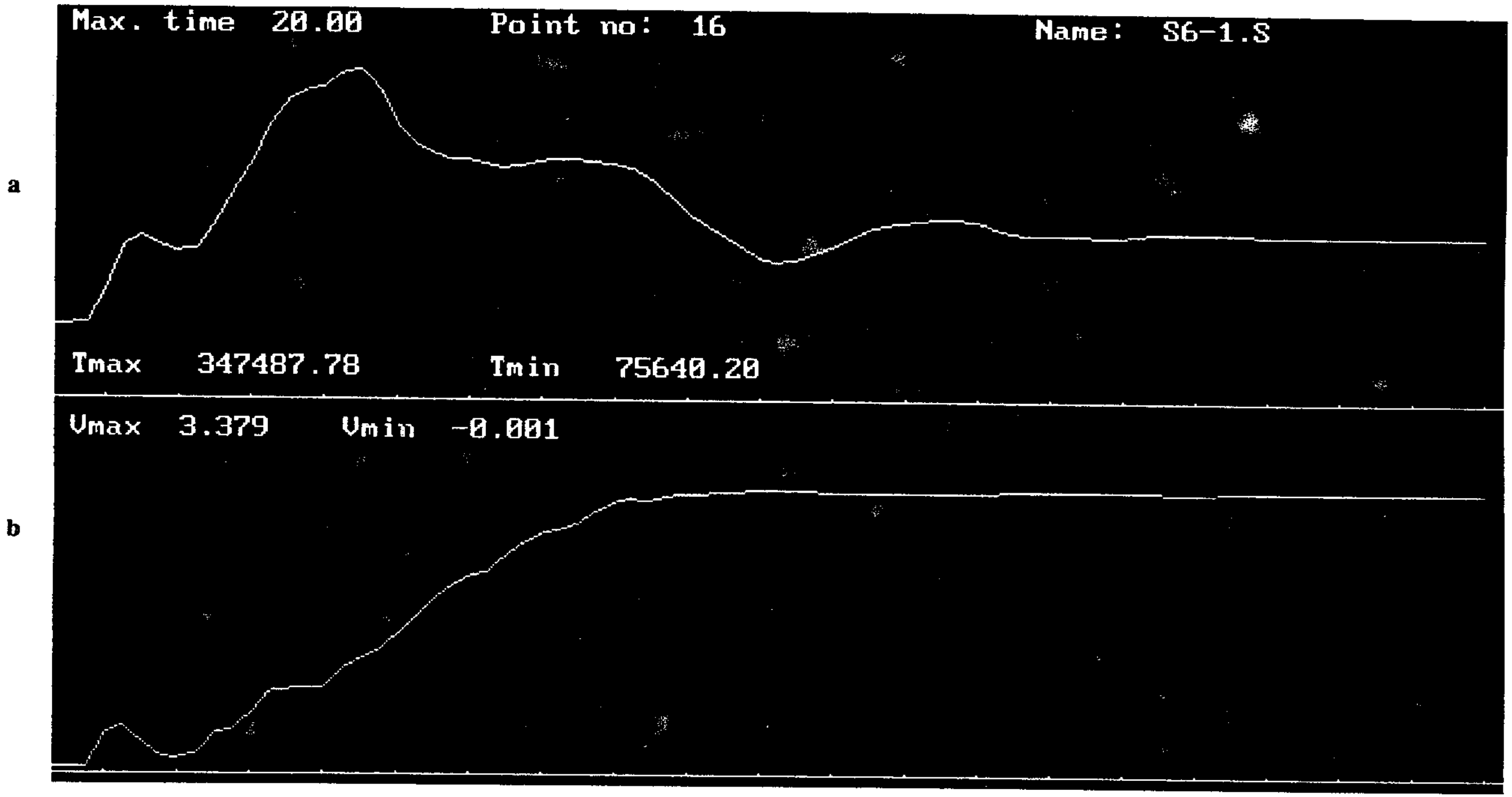
b



Empty start–up, fly wheels 4 x Te. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 16



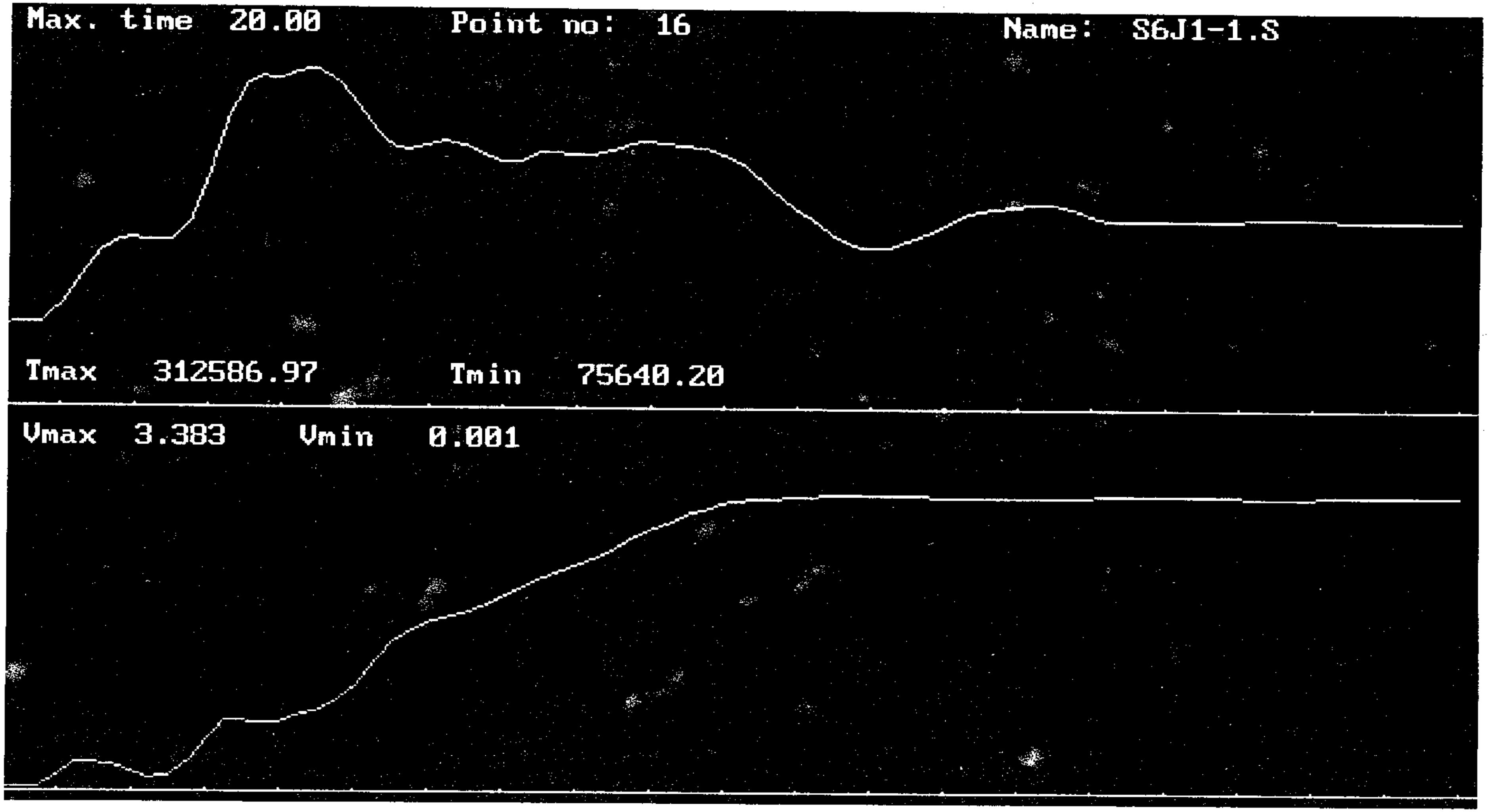
Fully loaded start–up, no fly wheels. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 17

a

b



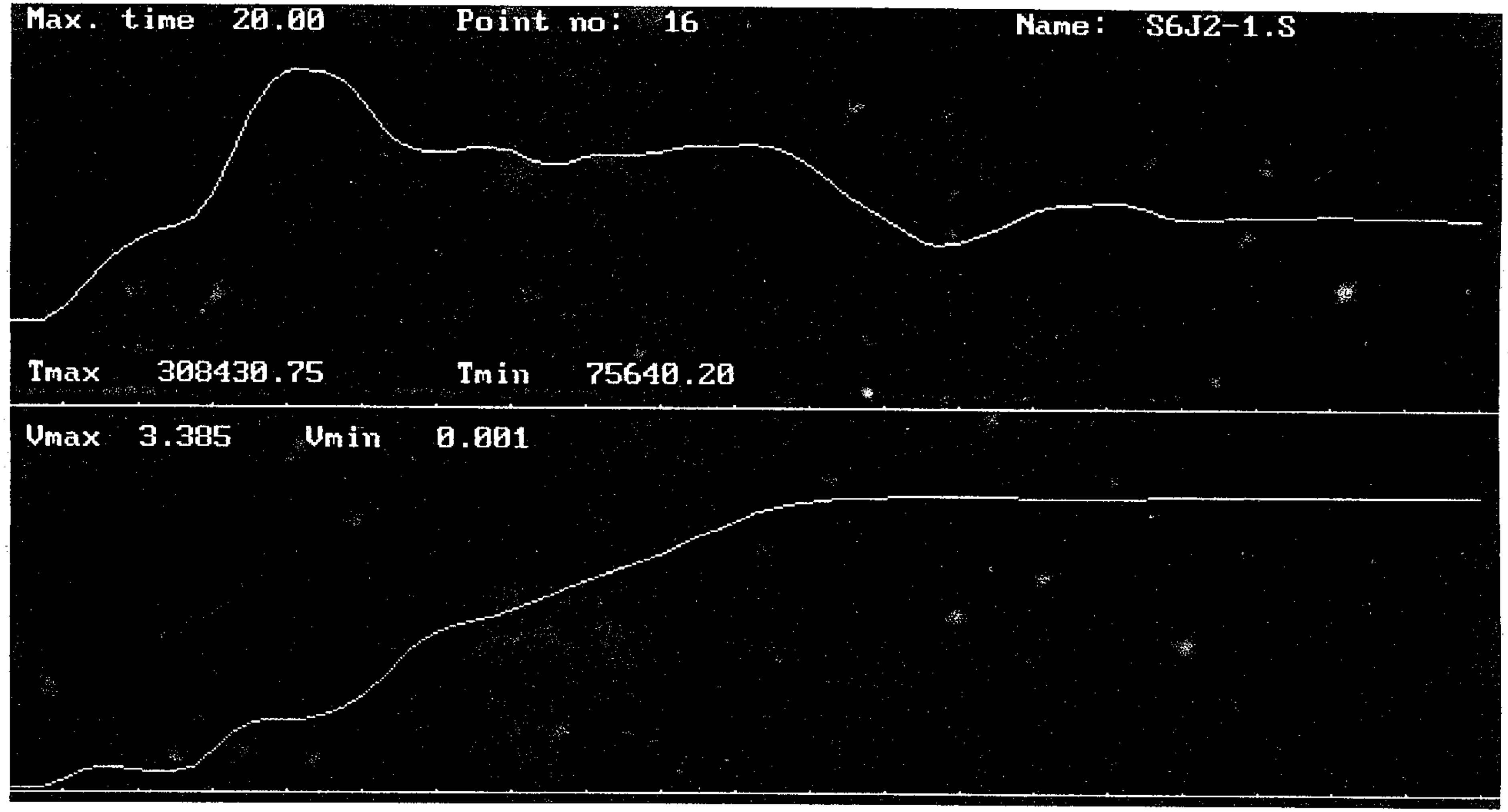
Fully loaded start–up, fly wheels 1 x 1e. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 18

a

b

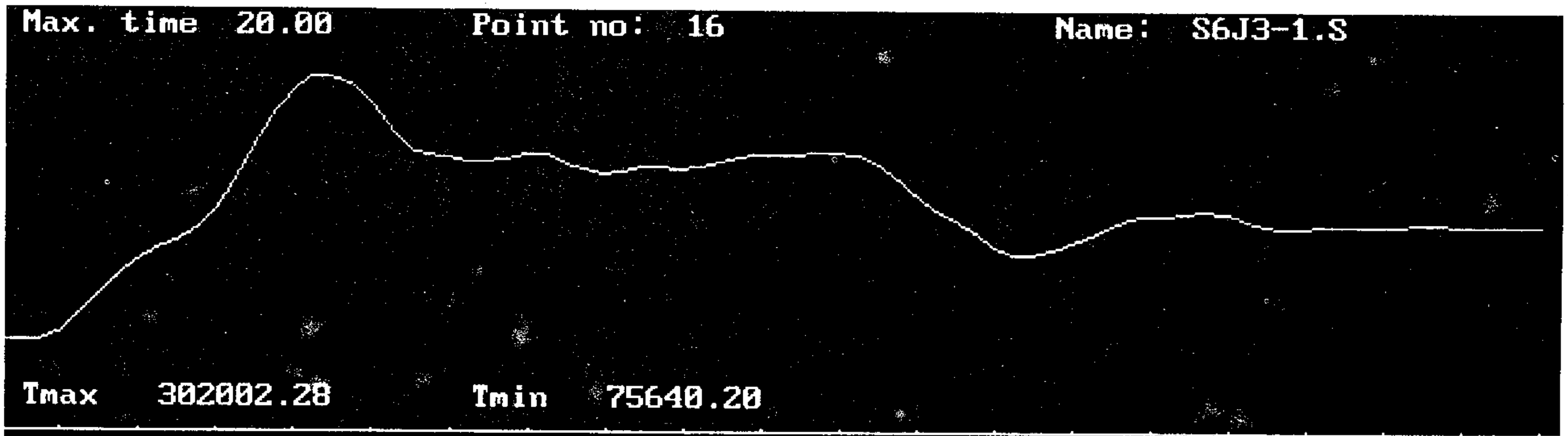


Fully loaded start–up, fly wheels 2 x 1e. Point close to the primary drive pulley

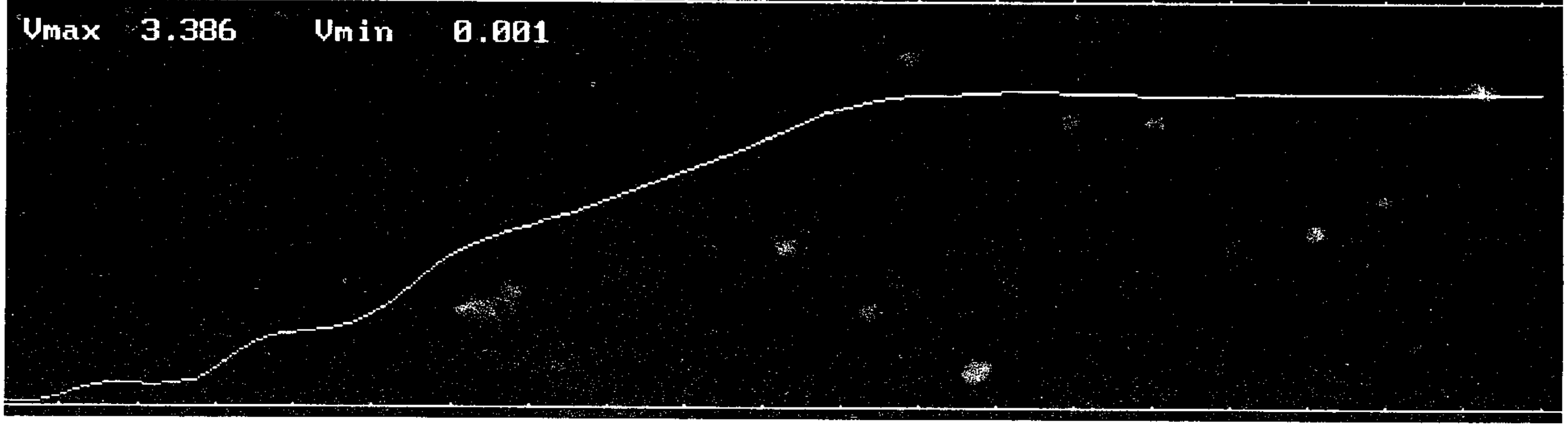
a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 19

a



b



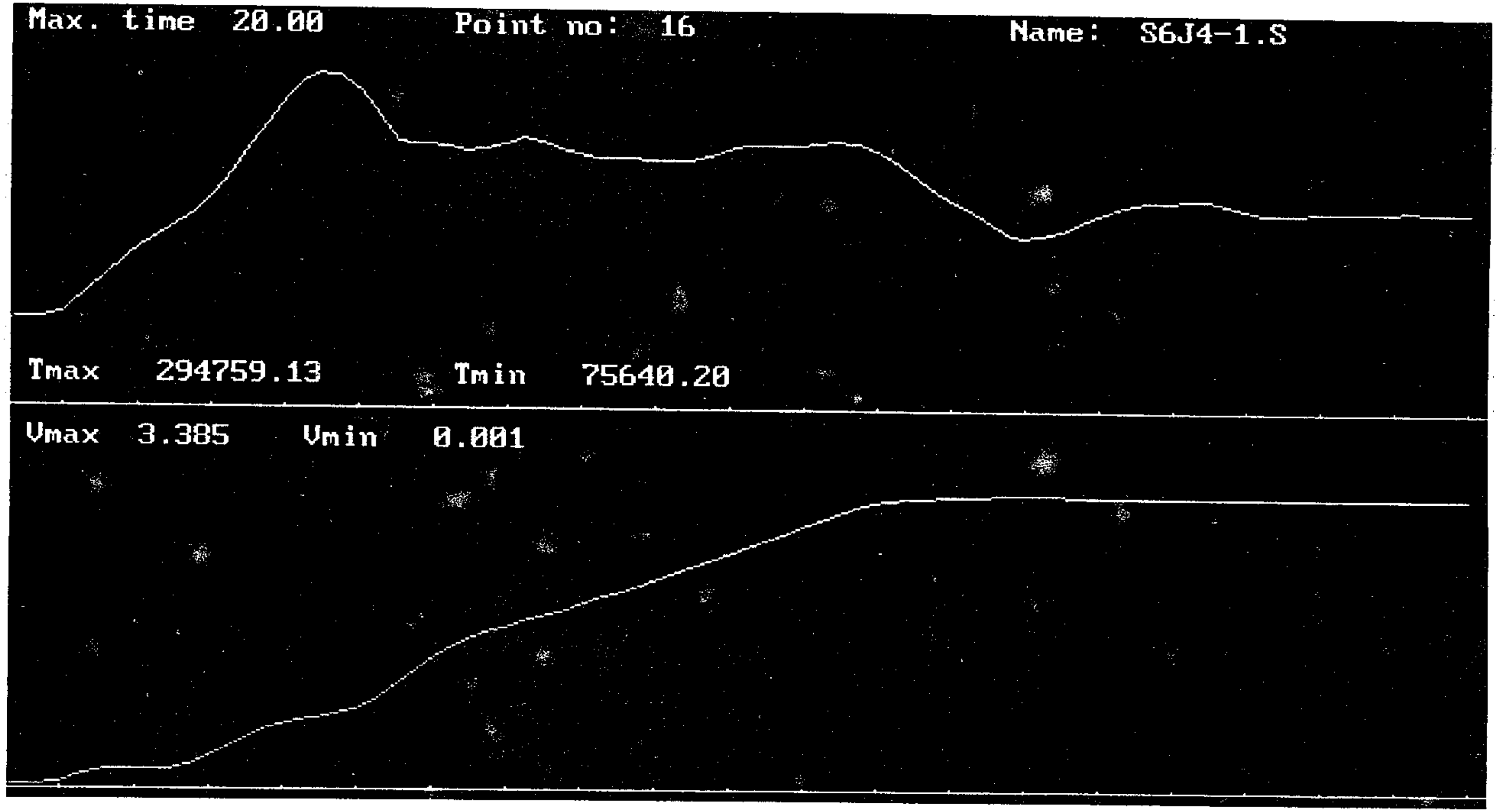
Fully loaded start–up, fly wheels 3 x Te. Point close to the primary drive pulley

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 20

a

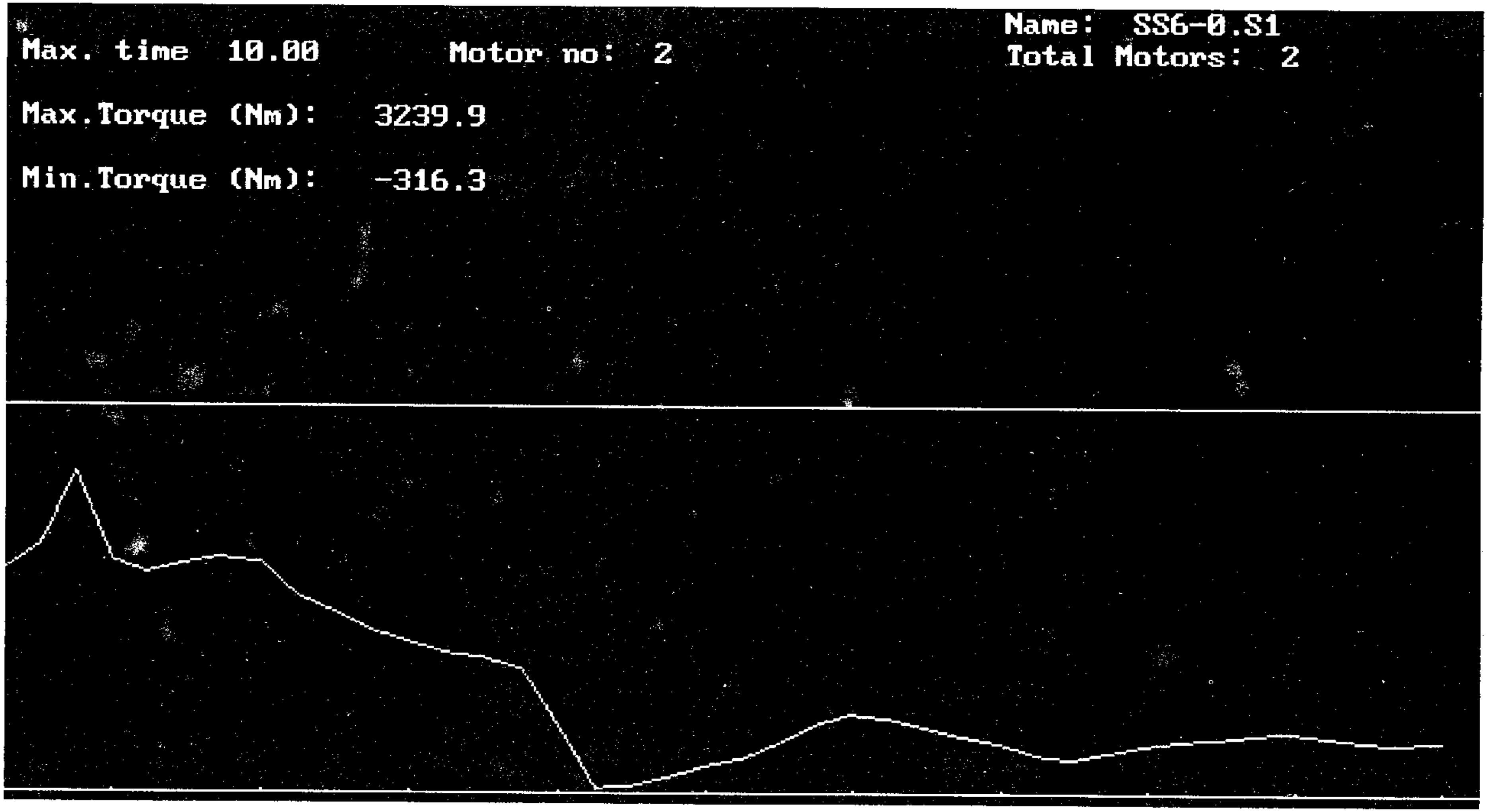
b



Fully loaded start–up, fly wheels 4 x Te. Point close to the primary drive pulley

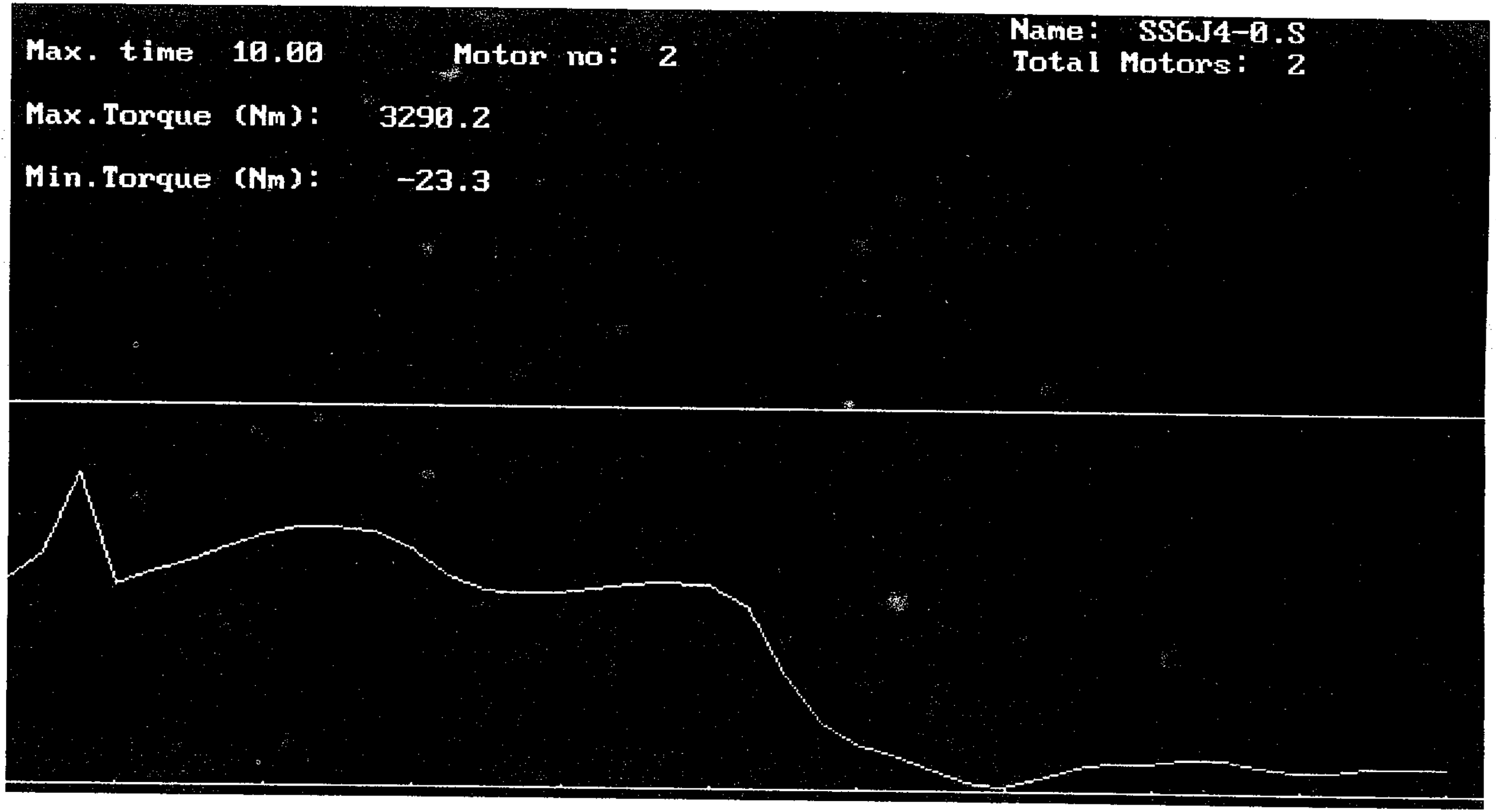
a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 21



Motor torque [Nm] during empty start-up, no fly wheel

FIGURE 22

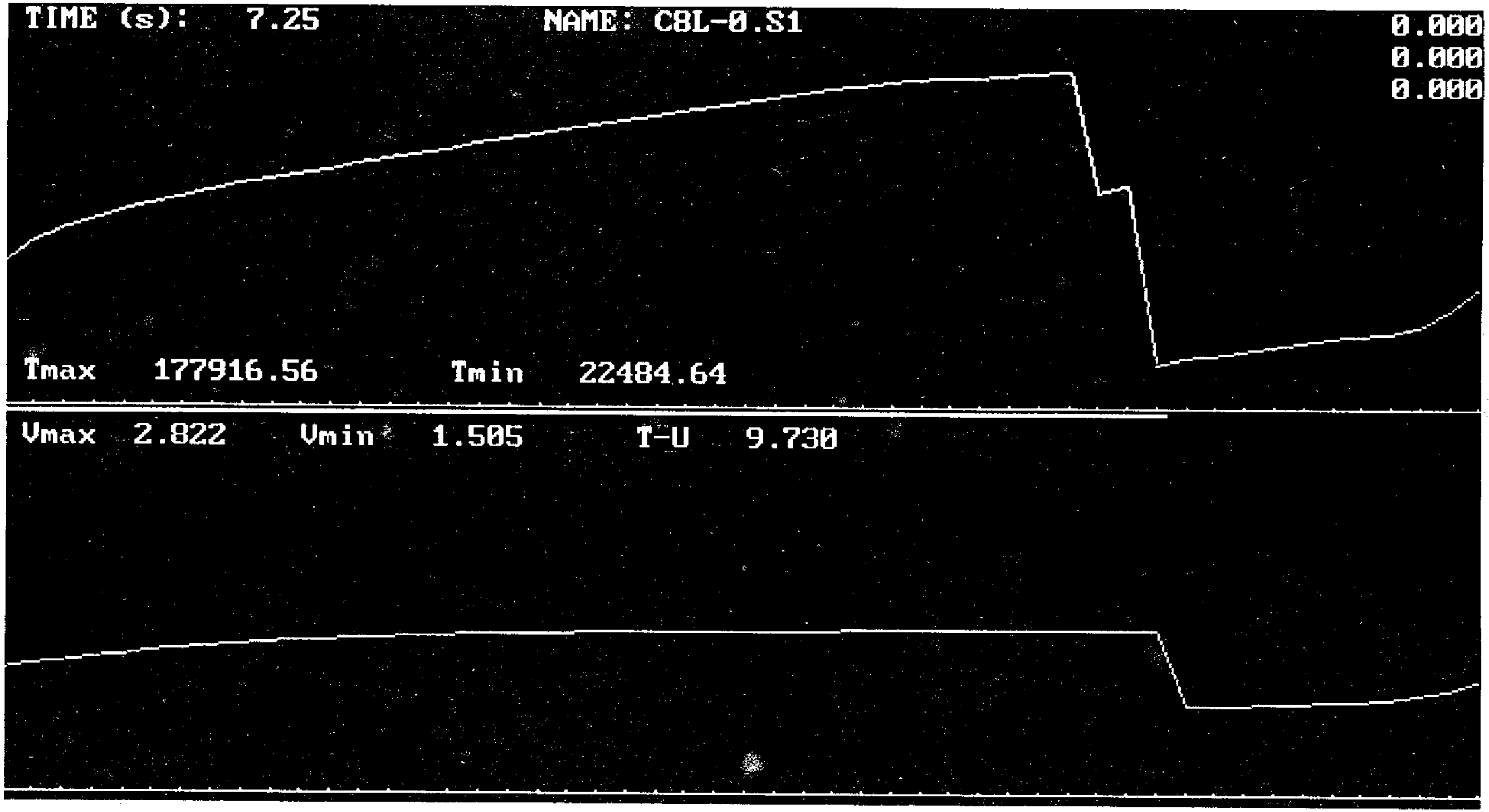


Motor torque [Nm] during empty start–up, fly wheel 4 x Te

FIGURE 23

a

b



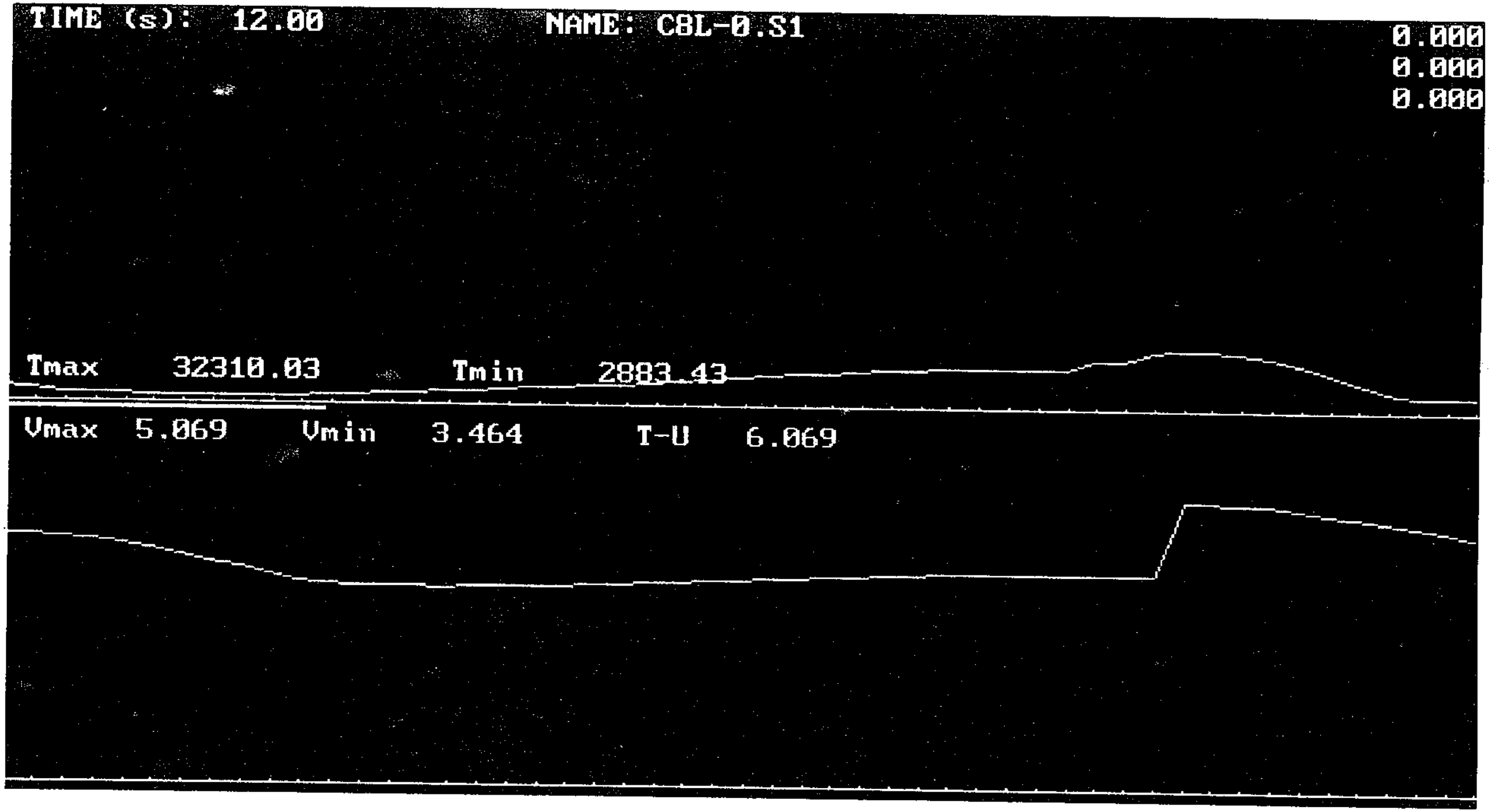
Empty start-up, no fly wheels (1,4 km long conveyor)

a. Graph of tension along the conveyor [N]
b. Graph of velocity along the conveyor [m/s]

FIGURE 24

a

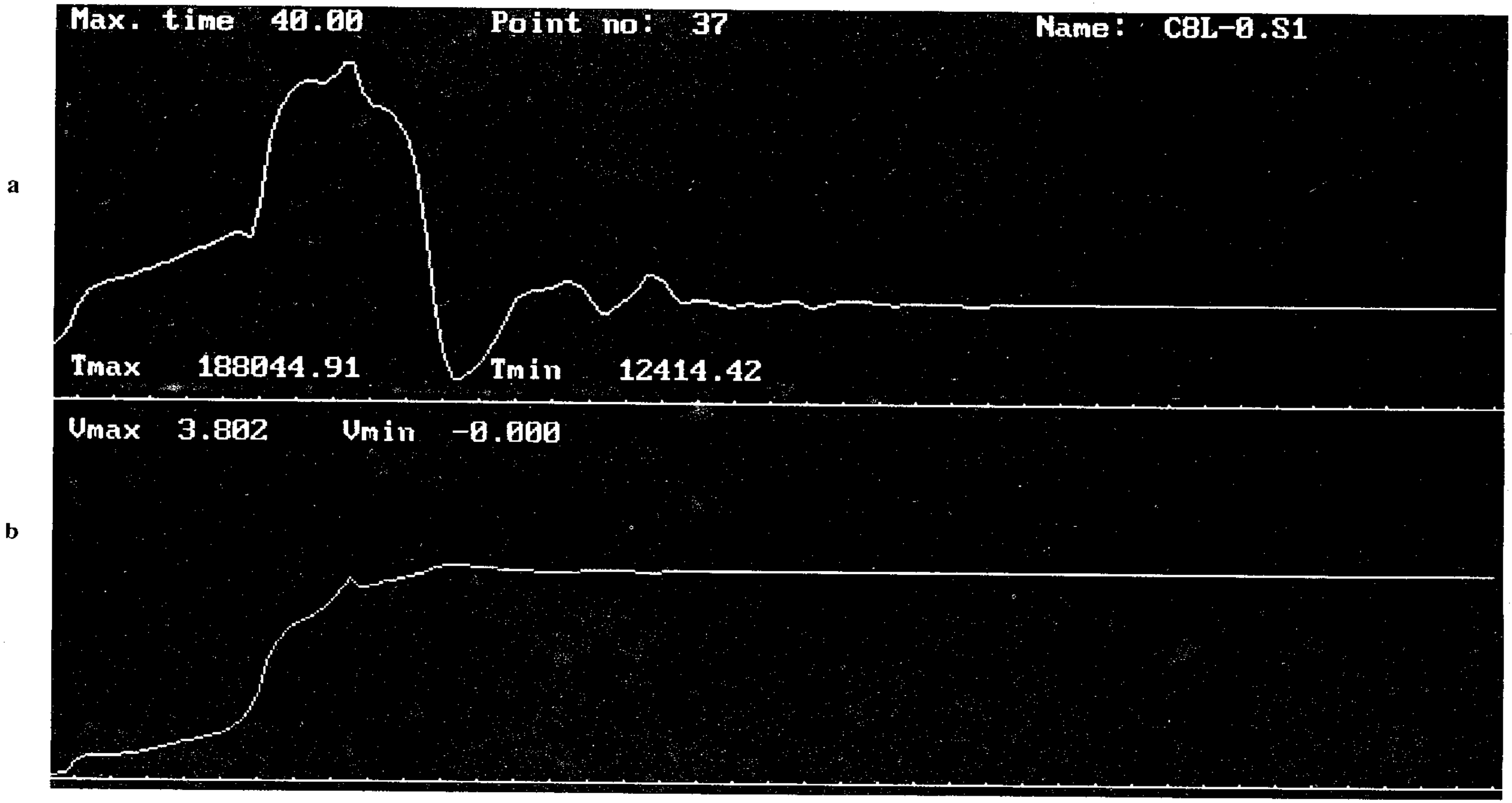
b



Empty start–up (final phase), no fly wheels (1,4 km long conveyor)

a. Graph of tension along the conveyor [N]
b. Graph of velocity along the conveyor [m/s]

FIGURE 25



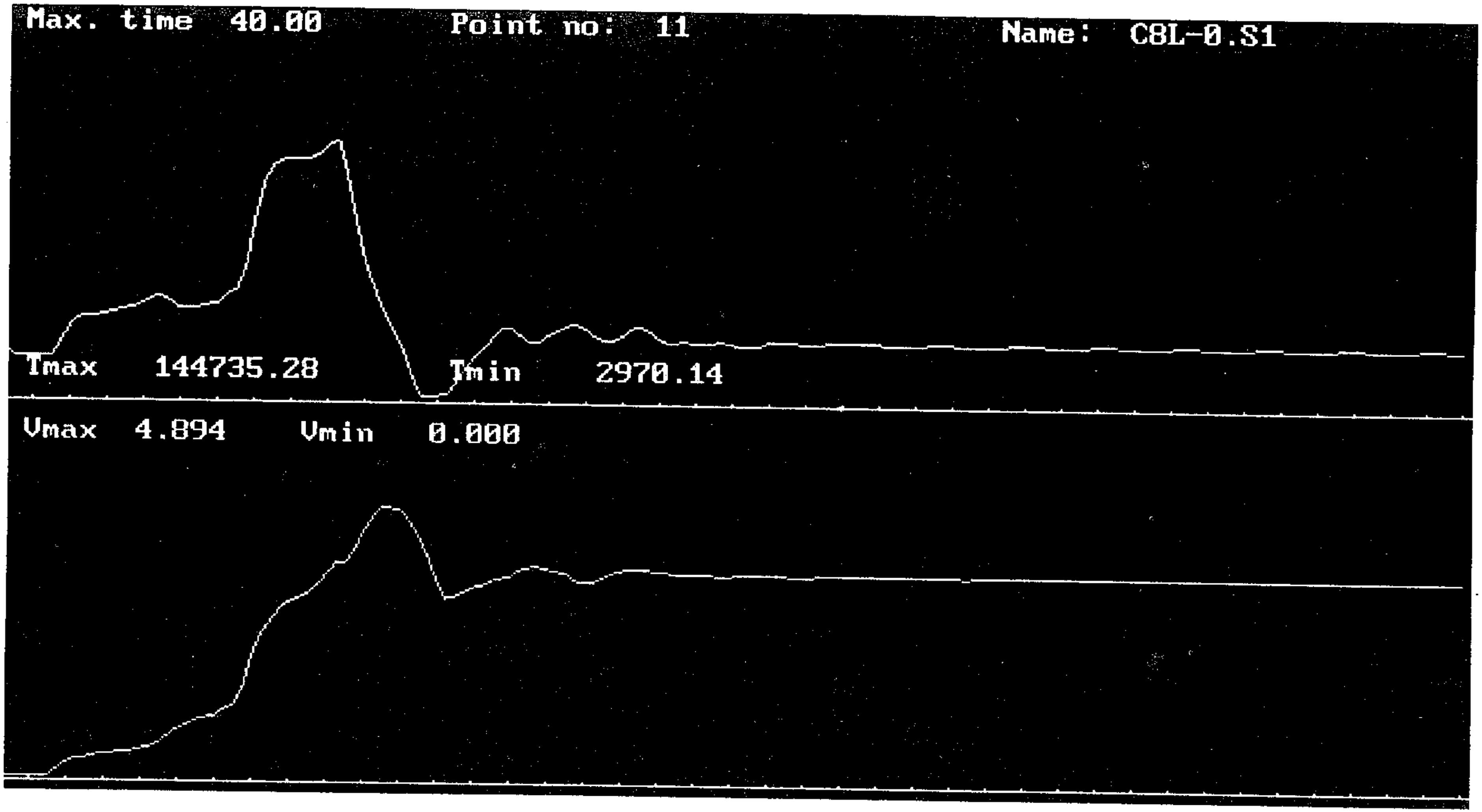
Empty start-up, no fly wheels. Point close to the primary drive pulley (1,4 km long conveyor)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 26

a

b



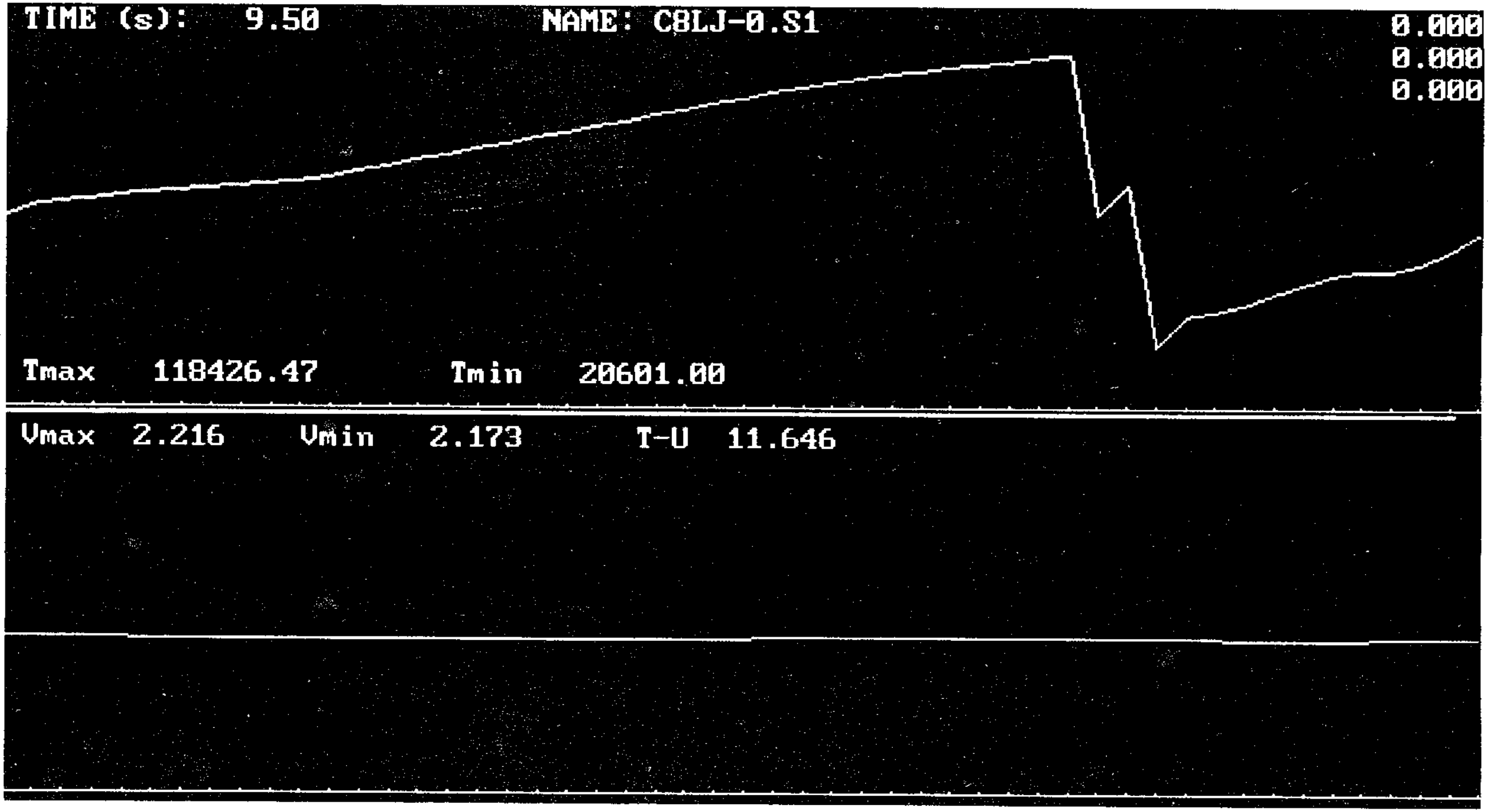
Empty start–up, no fly wheels. The lowest point of the conveyor profile (1,4 km long conveyor)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 27

a

b



Empty start–up, fly wheels (1,4 km long conveyor)

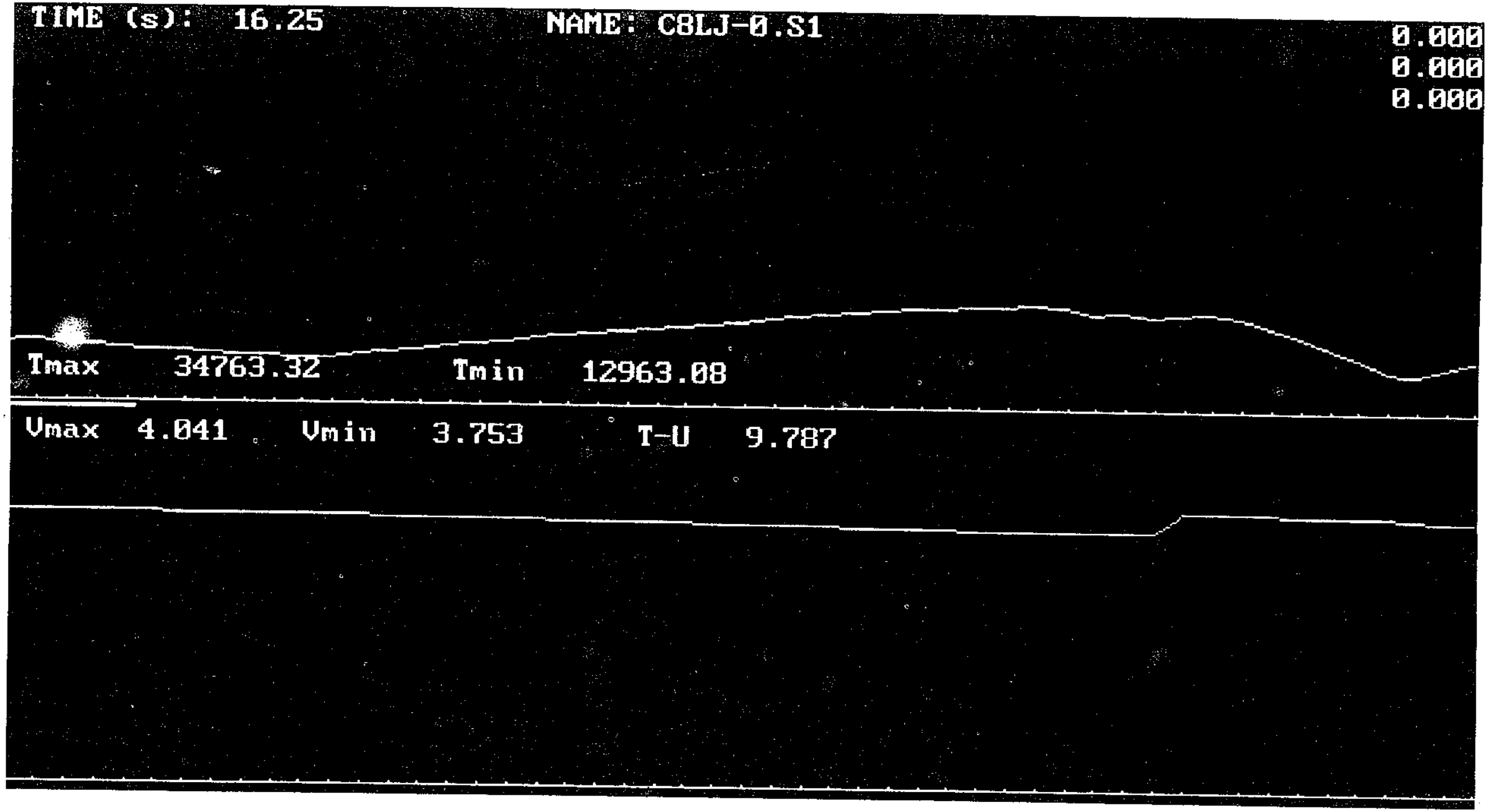
a. Graph of tension along the conveyor [N]

b. Graph of velocity along the conveyor [m/s]

FIGURE 28

a

b



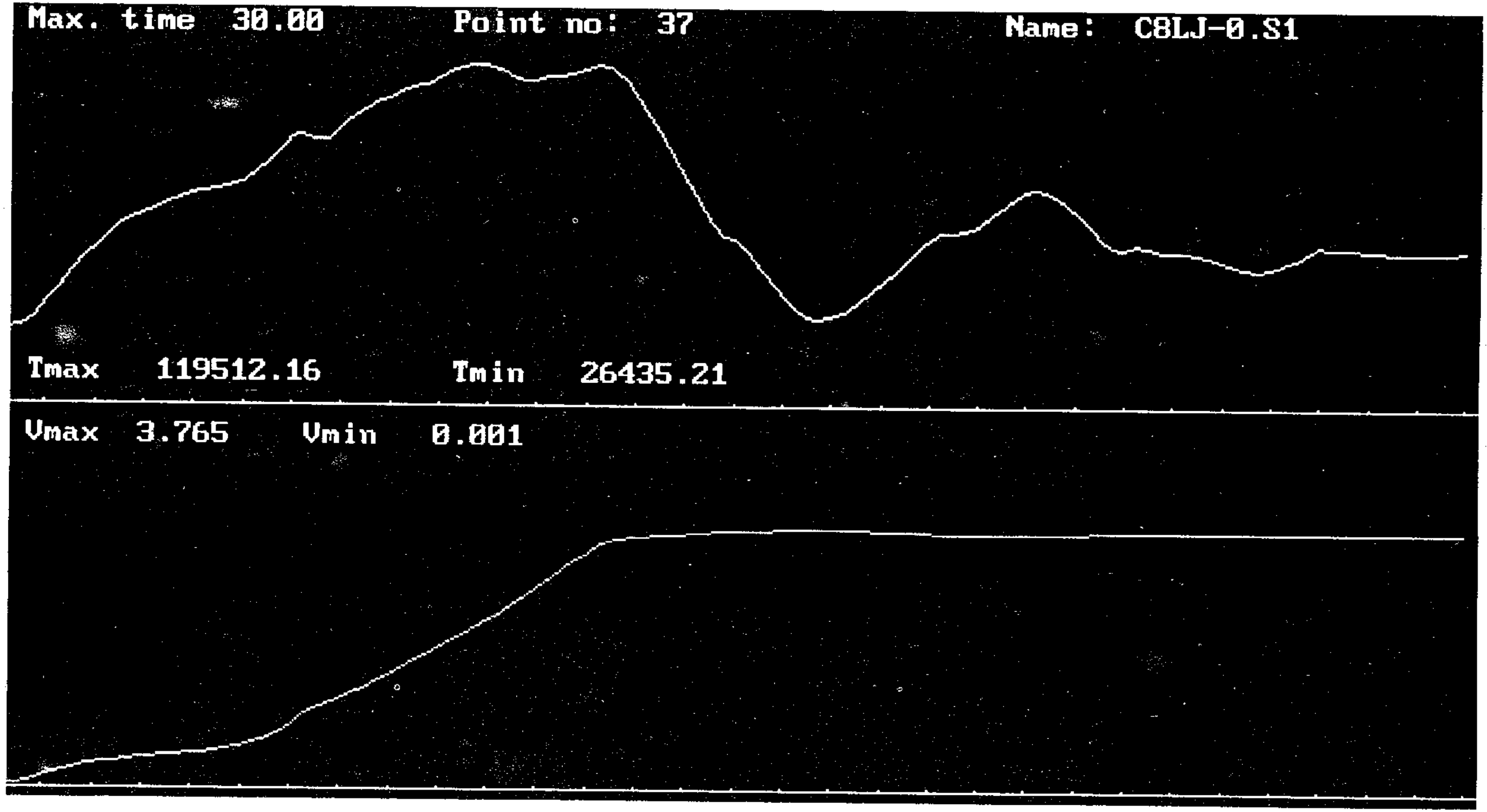
Empty start–up, fly wheels, final phase (1,4 km long conveyor)

a. Graph of tension along the conveyor [N]
b. Graph of velocity along the conveyor [m/s]

FIGURE 29

a

b



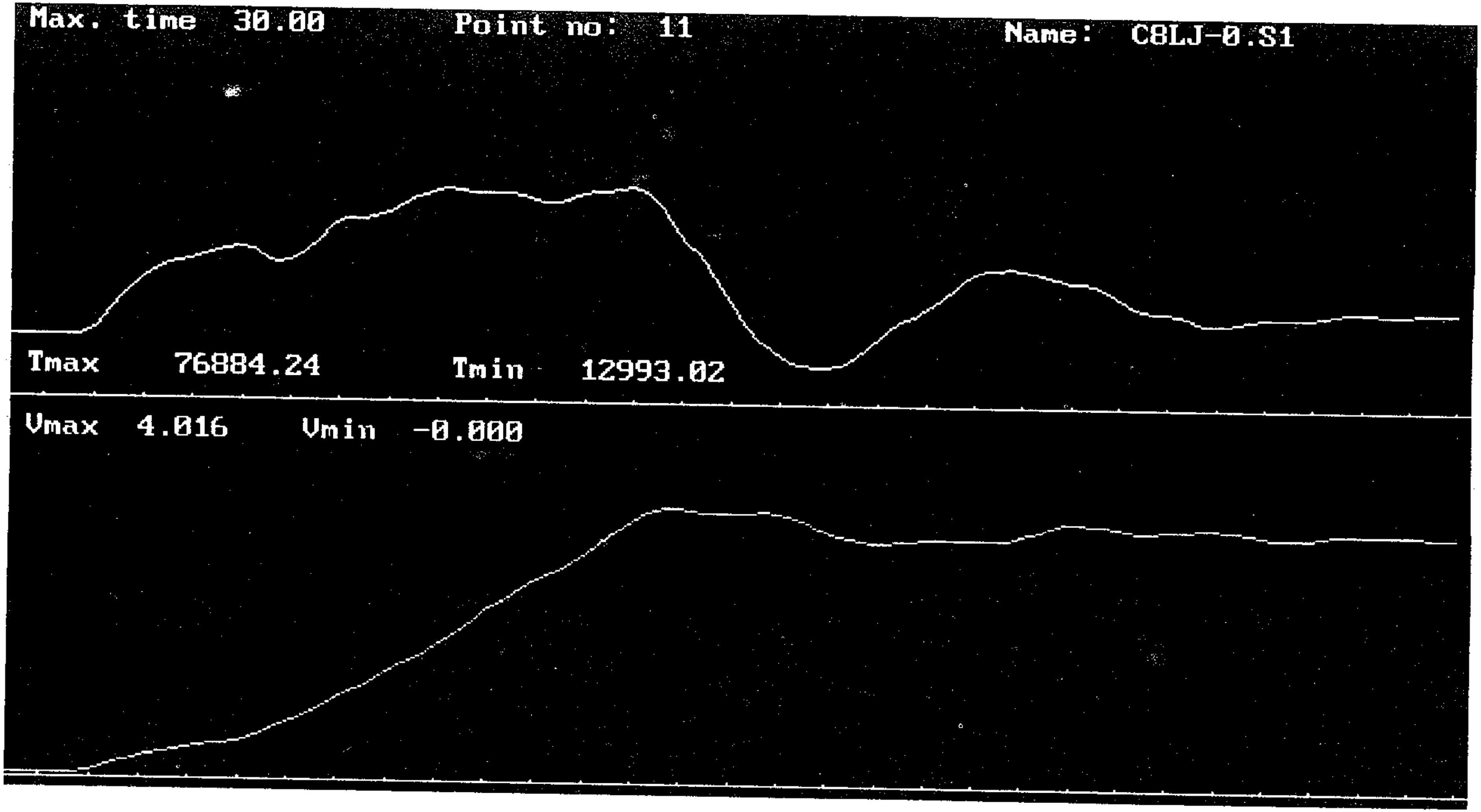
Empty start–up, fly wheels. Point close to the primary drive pulley (1,4 km long conveyor)

a. Graph of tension [N]
b. Graph of velocity [m/s]

FIGURE 30

a

b



Empty start-up, fly wheels. The lowest point of the conveyor profile (1,4 km long conveyor)

a. Graph of tension [N]

b. Graph of velocity [m/s]