Pressure Fluctuations in Mechanically Lined Pipelines During Reeling Operations

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***Abstract*—** Mechanically Lined Pipelines (MLP) have been widely adopted within the offshore energy industry as a cost-effective pipeline construction that can be installed subsea by any pipelay method with varying ease. When installing MLP by reel lay, the plastic deformation experienced by the pipe disrupts the balance of forces gripping the liner to the carrier pipe and can result in wrinkling of the liner. This wrinkling can lead to reduced corrosion resistance and operability of a line. Various methods to prevent this wrinkling have been studied in the past, such as increased MLP liner thickness and internal pressurisation. Internal pressurisation of MLP has become the industry established norm with a solid track record.

The installation method consists of filling the pipeline with a fluid and pressurising it to prevent wrinkling of the liner at any point during transport and installation by vessel. However, vessel movements due to the sea-state generate pressure waves which propagate in the fluid-filled pipeline, inducing high and low local pressure values. These variations in pressure may lead to damages to the internal liner of the pipeline.

A model to estimate the amplitude of pressure fluctuations during reeling is presented. The model relates the amplitude of pressure fluctuations in pipelines to the movement of the reel, defined by amplitude and frequency, based on dynamic simulations.

***Keywords*—**Pressure transients, Reel-lay pipeline installation.

I. INTRODUCTION

Management of internal corrosion in subsea pipelines, induced by impure hydrocarbon streams or CO_2 with impurities, can be active or passive. Active management of internal corrosion requires regular injection of corrosion inhibitor that will coat the inner wall of the pipeline. Passive management of internal corrosion is based on careful material selection.

Corrosion resistant alloys (CRA), such as stainless steels, are often recommended for passive management of corrosion. However, CRAs are between 1.6 and 2.5 times more expensive than carbon steel (CS), depending on the alloy composition. Therefore, pipelines requiring passive corrosion management are often fabricated from CS with a CRA liner, as the inner layer in contact with the fluid.

Mechanically lined pipelines have been widely adopted within the oil and gas/CCS industry as a cost-effective solution for corrosion management and can be installed using any of the industry standard pipelay methods with varying ease. For instance, reeling of mechanically lined pipelines is similar to the reeling of CS pipelines but requires internal pressurisation in order to prevent wrinkling of the CRA liner.

Setting and maintaining the internal pressure of a mechanically lined pipeline (commonly above 40 bar(a)) is required to prevent wrinkling of the CRA liner. However, the internal pressure must remain below the design limit of the pipeline. Therefore, it is important to set an internal pressure that will always remain between the minimum pressure and design pressure.

A general overview of mechanically lined pipes and reeling operations is presented first. Then, an actual pressure measurement obtained during the reeling operation is analysed, and each component investigated individually. In particular, dynamic pressure fluctuations are modelled and simulated. Simulation results are then discussed, and practical recommendations are presented, with regards to reeling of mechanically lined pipes.

II. MECHANICALLY LINED PIPELINES

Corrosion Resistant Alloys (CRA) are often used for rigid pipelines and piping where corrosive fluids may be used. Two main forms of CRA lined pipes are:

- Metallurgically bonded where there is a bond between layers at an atomic level;
- Mechanically lined where the layers are held together by mechanical forces only.

Mechanically Lined Pipe (MLP) is a cheaper alternate to metallurgically bonded pipe due to its lower processing costs and manufacturing route.

Mechanically Lined Pipes are manufactured as separate carbon steel (CS) and CRA pipes initially. The CRA liner is then inserted into the CS carrier pipe, and the pipes are expanded using hydrostatic pressurisation typically. The subsequent contraction mechanically presses the liner to the carrier pipe. The liner is then sealed to the carrier pipe at its ends through welding.

MLP has been widely adopted within the industry as a cost-effective solution and can be installed using any of the industry standard pipelay methods with varying ease.

III. REELING OPERATIONS

Plastic deformation of the pipeline during reel-lay disrupts the balance of forces of the CRA liner pressing against the CS carrier pipe. The force imbalance between the two layers can

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result in wrinkling of the liner, internal buckling and potential damages (cracks) of the liner, and reduction in flowing area. Thus, force imbalances can lead to reduced in corrosion resistance and operability of the pipeline.

Wrinkling of the liner during reel-lay can be prevented by various methods such as increasing the thickness of the liner or internal pressurisation. Internal pressurisation consists of filling the pipeline with water and pressurising it to prevent wrinkling of the liner at any point during the spooling and the offshore installation. Internal pressurisation of MLP has become the industry established norm with a solid track record.

The internal pressure in the pipeline as it is spooled and unspooled is not static and several parameters are likely to contribute to fluctuations. The SAIPEM Constellation pipelay vessel is shown in Fig. 1 and a schematic representation of its installation mechanism, including reel, aligner wheel and tensioner is shown in Fig. 2. The reeled rigid pipeline is unreeled first, then bent over the aligner wheel before being straightened in the lay tower.

Thus, a mechanically lined pipe installed via the reel-lay method is subjected to a series of bend cycles. It is important that the internal pressure is maintained above a minimum value in order to prevent liner wrinkling. An example of pressure measurement in a 16 inch mechanically lined pipe as it is being shipped (1 and 2) then reel-layed (4 and 5) is shown in Fig. 3. Note that actual values of pressure and time are not shown for confidentiality purposes.

The pressure signal includes a sharp increase (1) that was due to a planned increase in pressure in the pipeline by injection of additional water. The slow decrease in pressure (2) spans nearly 24 hours and is explained by the cooling-down of the water-filled pipeline as it is being transported offshore. The sharp decrease in pressure (3) was accidental and rapidly mitigated by repressurisation prior to the start of reel-laying. The reeling operation itself includes a slow decrease in pressure (4) and rapid pressure oscillations (5).

Fig. 1 SAIPEM Constellation pipelay vessel

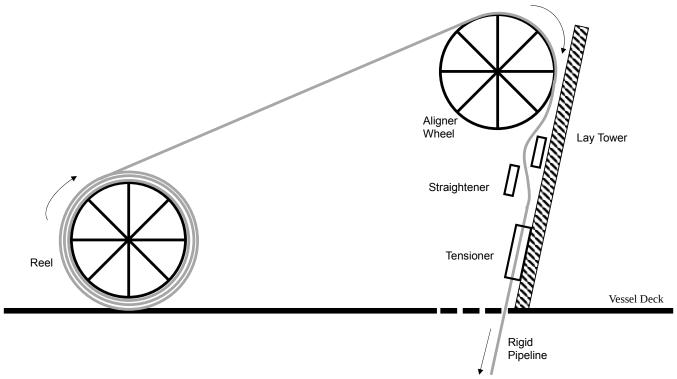

Fig. 2 Schematic representation of reel-lay mechanism

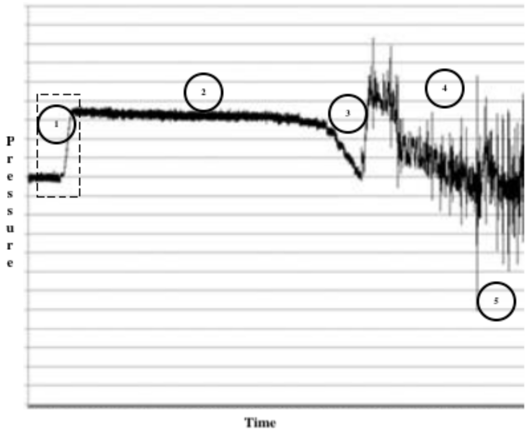

Fig. 3 Example of pressure measurement in mechanically lined pipe during reeling operation of a 16 in pipeline

IV. QUASI-STATIC PRESSURE DROP

The slow decrease in pressure observed previously is the result of two different mechanisms that occur during the reeling of the pipeline.

The first mechanism is the elongation of the pipeline due to the bending cycles. The pipeline elongates by approximately 1,000th of its initial length (circa 3 metres) as it is spooled, unspooled, passes over the aligner wheel, through the straightener and is laid on the seabed. Elongation due to self-weight as the pipe, as it's being lowered through the water column, depends on the water depth and is generally on the order of tenths to hundredths of metres (< 1 metre). Therefore, elongation of the pipeline due to its weight is considered negligible.

The quasi-static pressure drop in the water-filled pipeline can be calculated using the properties of water [1] and Eq. (1). The density and isothermal compressibility (inverse of bulk modulus) of water are shown in Fig. 4 against water depth, assuming a linear thermal gradient from 20°C at sea level to 5°C at seabed (common at 1,000 m water depth). A 15°C gradient in water temperature leads to changes in density and isothermal compressibility across the pipeline in the order of 10 kg/m^3 and 10^{-11} Pa^{-1}, respectively (Fig. 4, [1]).

$$\beta = -V\frac{\Delta p}{\Delta V} \tag{1}$$

A single reel contains circa 2,900 m of 16 in pipeline. Thus, a bending cycle elongation of 2.9 m is expected, which leads to a reduction in pressure of approximately 9 bar. Note that any change in ovality due to successive plastic deformations would have a negligible impact on the overall cross-section area of the pipeline. Hence, changes in pressure related to changes in the pipeline ovality are not considered.

The second mechanism is the cooling of the water-filled pipeline to the seawater conditions. Changes in fluid temperature inside the water-filled pipeline are technically a dynamic effect. However, the static nature of the water contained in the pipeline limits the heat transfer with the ambient medium (air above sea level and seawater below) through the pipe wall. A cool-down time of approximately 1°C per hour has been calculated, which is orders of magnitude less than the pipeline movement (circa 3 km/d).

Considering constant coefficients of thermal expansion and isothermal compressibility for water of 0.000207°C^{-1} and 4.5 10^{10} Pa^{-1}, respectively, a 15°C decrease in temperature leads to a change in volume of -0.0031 m^3/m^3 and a pressure reduction in the order of 10^{-12} bar. Cooling of water contained in the pipeline over a prolonged period of time leads to an insignificant decrease in pressure.

Therefore, the main contribution to the quasi-static pressure drop is the pipeline elongation due to the successive bending cycles.

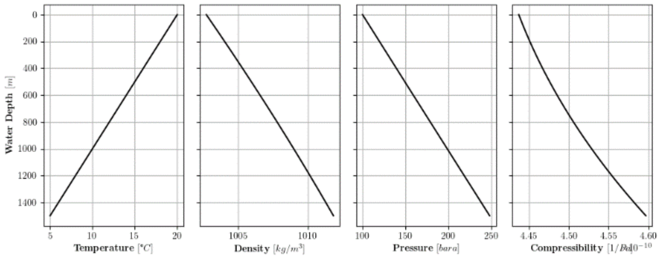

Fig. 4 Water temperature, water density, pressure in water-filled pipeline and water isothermal compressibility

V.RAPID PRESSURE FLUCTUATIONS

Given restrictions due to the data confidentiality, results presented in the following sections are obtained from synthetic cases rather than the actual installation parameters that led to the pressure trace shown in Fig. 3.

A. Vessel Motion

The sea state drives the motions of the lay vessel and results in six (6) degrees of freedom for the pipeline: yawing, swaying, pitching, heaving, rolling and pipe surging. The water contained in the pipeline adds two (2) degrees of freedom: fluid surging and breathing [3].

For the purpose of this study, only pipe surge in the direction of the lay tower is being considered. The water-filled pipeline is therefore represented as a one-dimensional system where interactions of pressure waves induced by motions around other axes are neglected. The tensioner (Fig. 2) is considered as the excitation point.

The repetitive motion of the vessel due to the sea state induces pipeline oscillations and changes in fluid velocity inside the pipeline. The change in internal fluid velocity is approximated assuming that the pipeline movement is oscillatory, such that the fluid velocity profile can be described using Uchida's theoretical model ([5] & [6]). Note that this is an approximation since Uchida's model describes the oscillations of a fluid in a stationary pipe, whereas the pipeline oscillates too during reeling operations.

Fluid velocity profiles for oscillating periods of 2 s (0.5 Hz), 5 s (0.2 Hz) and 15 s (0.067 Hz) are shown in Fig. 5 over the course of one period. Results show that the velocity profiles are typical of turbulent flows (square-shaped) and nearly fully developed by the time they reverse. Results also indicate that the oscillation period has a minimal impact on the velocity profile over the range considered.

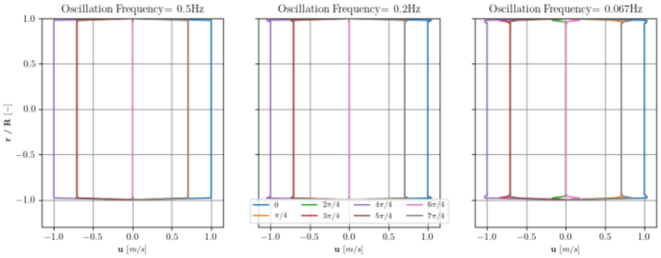

Fig. 5 Velocity profiles during one cycle of oscillation with oscillation frequency

Propagation of the pressure waves induced by the vessel motions is simulated using a commercial one-dimensional dynamic multiphase-flow solver commonly used in the energy industry: OLGA (version 2020.1). The fluid properties are modelled using the IAPWS equation of state [1], considering pure water.

The pipeline wall is modelled as separate layers of corrosion resistant alloy (CRA), carbon steel (CS), and fusion bonded epoxy (FBE) used as an external coating. Each layer is defined by a thickness, a material density, heat capacity, thermal conductivity and Young's modulus of elasticity. Mechanical parameters of the model are presented below.

TABLE I
Material properties for modelling of 16 in mechanically lined pipeline

Parameter	CRA	CS	FBE
Thickness [mm]	3.0	22.2	3
Inner Diameter [mm]	381.0	387.0	431.4
Density [kg/m3]	8,440	7,850	1,400
Heat Capacity [J/kg.°C]	500	500	1,000
Thermal Conductivity [W/m.°C]	25	45	0.3
Young's Modulus [Pa]	190.10^9	205.10^9	200.10^9

The pipeline geometry is modelled in one dimension. The geometry starts with a 500-metre-long straight line first that represents the length around the reel up to the top of the aligner wheel (Fig.2). The geometry ends with a minimum length of 500 metres laid on the seabed. The pipeline geometries are shown in Fig. 6.

Three geometries are considered, based on the water depth for installation: 250 m, 500 m and 1,000 m, with the corresponding pipeline lengths: 1,351 m, 1,942 m and 2,413 m, respectively. The pipelines are closed at both ends such that the natural wave propagation periods (2.L/a) for the three cases modelled are 1.8 s, 2.6 s and 3.2 s, respectively with ρ=1,000 kg/m^3 and a=1,500 m/s.

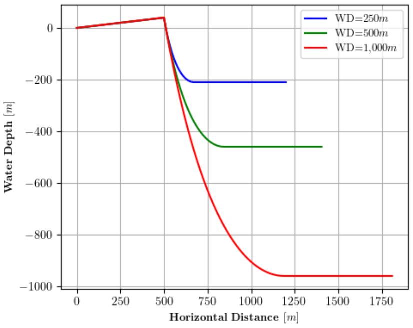

Fig. 6 Pipeline geometries

B. Regular Waves

Regular waves refer to continuous oscillations of the vessel that can be described by a single sea-wave period and amplitude. The amplitude of the sea-wave is described by the maximum oscillation velocity. Numerical simulations are performed for a range of wave periods and amplitudes:

- Oscillating Period [s]: 2 s, 4 s, 6 s, 8 s, 10 s, 15 s;
- Amplitude [m/s]: 0.01 m/s, 0.025 m/s, 0.05 m/s, 0.1 m/s, 0.25 m/s, 0.5 m/s, 1.0 m/s.

Propagation of a single pressure wave (one oscillation) in the pipeline is simulated first for the three geometries considered, considering an initial pressure of 75 bar(a) with oscillation amplitude and period of 1.0 m/s and 6 s, respectively (Fig. 6). Results show that the initial pressure wave generated by the change in fluid velocity is approximately 15 bar in amplitude (1,000 m case). This matches the value calculated using Joukowski's expression ([7] with ρ=1,000 kg/m^3, a=1,500 m/s and Δu=1 m/s):

$$\Delta p = \rho a \Delta u \tag{1}$$

Note that the oscillation period considered (6 s) is greater than the natural wave propagation periods of the pipeline geometries modelled (3.2 s). That is, the front of the pressure wave travels to the pipeline end, reflects and arrives back at the pipeline inlet (on the vessel) before the end of the oscillation in fluid velocity. Therefore, the front and tail of the pressure waves superimpose across the entire pipeline in general, and at its ends in particular. This explains why the minimum pressure reached for the 250 m and 500 m cases exceed the 15 bar initial Δp expected (Fig. 6).

Results also show that the pressure attenuation follows the expected damping pattern. This is a practical confirmation that the piece of software used for the study can now simulate fast transients, which were not possible to analyse numerically with earlier versions (prior to 2017). Note that the amplitude of the attenuation has not been benchmarked against actual data.

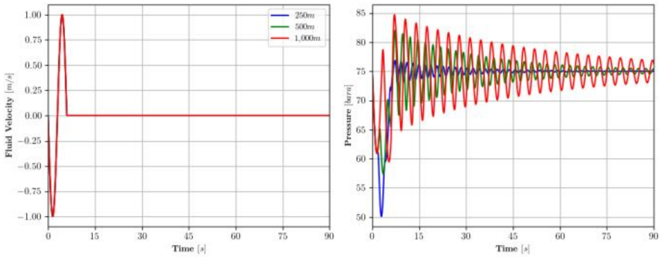

Fig. 7 Pressure and fluid velocity at the pipeline inlet during single oscillation (pressurisation=75 bar(a), oscillation velocity=1.0 m/s, oscillation period=6 s)

Propagation of continuous regular waves are simulated for all the pipelines, oscillation amplitudes and periods considered. Each simulation is performed for a duration of 30 s. An example of inlet fluid velocity and inlet pressure is shown in Fig. 8. The minimum and maximum pressures are also shown and illustrate the range of pressures expected during the reel-lay process. The minimum and maximum pressures are measured at the top of the aligner-wheel and at seabed, respectively.

Minimum pressures reached in the pipeline are shown in Fig. 9 for three levels of pressurisation of the water-filled pipeline (1,000 m water depth case). Results show an overall increase in minimum pressure with the level of pressurisation. Results also show an overall linear decrease in minimum pressure with increasing oscillation periods and amplitudes with a sharp peak for an oscillation period of 3 s.

The oscillation period of 3 s corresponds to the natural wave propagation periods in the water-filled pipelines considered in this analysis. Coincidence of the oscillation and natural wave propagation periods maximises the superposition of the waves close to the pipeline inlet. The minimum and maximum pressures are measured at the top of the aligner-wheel and at seabed, respectively.

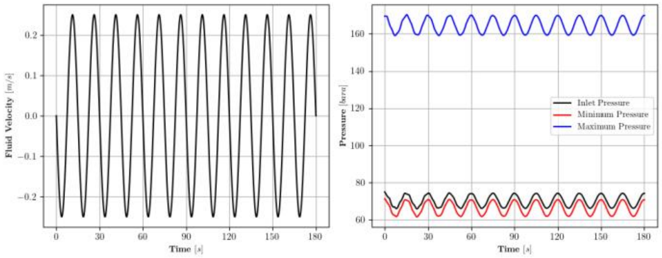

Fig. 8 Pressures and fluid velocity at pipeline inlet for WD=1,000 m (pressurisation=75 bar(a), oscillation velocity=0.25 m/s, oscillation period=6 s)

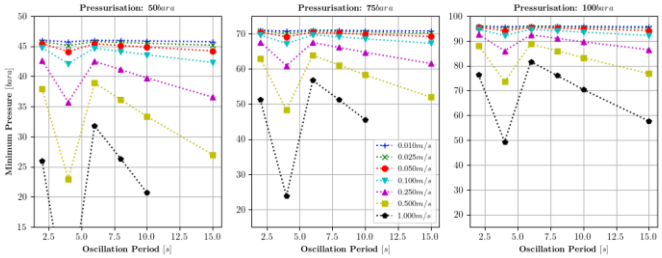

Fig. 9 Minimum pressure in pipeline against oscillation period with pressurisation level (WD=1,000 m)

Minimum pressures reached in the three pipelines considered are shown in Fig. 10 for pressurisation of the water-filled pipeline to 75 bar(a). Results show an overall increase in minimum pressure with the increase in water-depth/length. Results also show an overall linear decrease in minimum pressure with increasing oscillation periods and amplitudes with a sharp peak for an oscillation period around 3 s. As previously observed, the sharp peak in minimum pressure occurs when the oscillation and natural wave propagation periods coincide.

It should be noted that short oscillation periods are commonly associated with smooth sea state or small oscillation velocities. Therefore, increasing the pipeline steady state pressure prior to the start of the unreeling and installation process should minimise the risk of low-pressure peaks and damage to the liner.

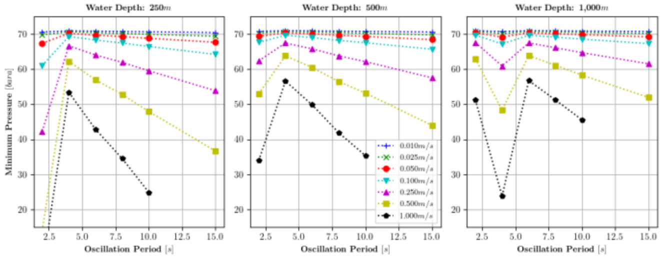

Fig. 10 Minimum pressure in pipeline against oscillation period with water depth (pressurisation level=75 bar(a))

C. Irregular Waves

Results above focused on regular waves defined by a single amplitude and period. However, sea-states vary continuously. The fluid velocity induced by the sea-states and the corresponding pressure signals recorded at the top of the aligner wheel are shown in Fig. 11 and 12, for two cases considered.

Results show that for the two cases considered, the minimum pressures are nearly constant as the sea undulations induce pressure waves that superimpose on each other and minimise the dynamic fluctuations inside the pipeline. Nevertheless, results show that the minimum pressure in the pipeline is maintained for long periods of time rather oscillating as shown in Fig. 8.

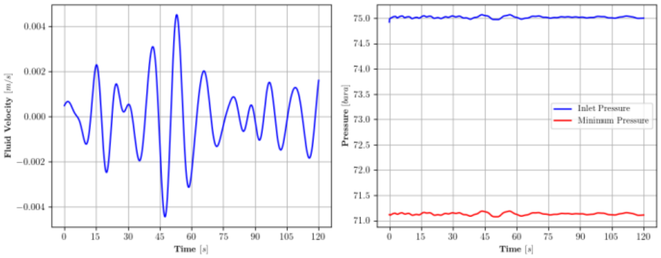

Fig. 11 Minimum pressure in pipeline due to irregular waves, Case 1

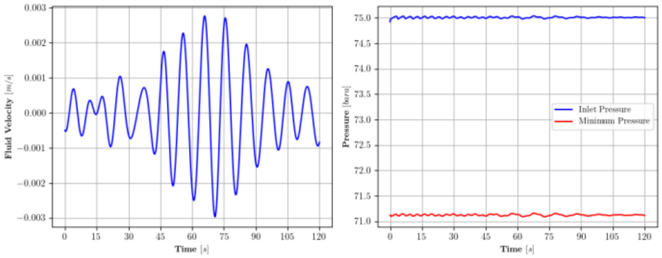

Fig. 12 Minimum pressure in pipeline due to irregular waves, Case 2

VI. CONCLUSIONS

Results have shown that pressure fluctuations in mechanically lined pipelines during reeling operations are caused by several phenomena. The pipeline elongation that results from the reeling / unreeling cycles and the lowering to the seabed lead to a quasi-static pressure drop. Thermal effects that occur during the installation process can often be neglected. However, large dynamic pressure fluctuations result from the motion of the vessel in response to the sea-state.

Pressure fluctuations are the result of pressure waves induced by the oscillation of the vessel and propagate across the pipeline. The pressure extrema in the pipelines are driven by the superposition of multiple waves that propagates back and forth in the water-filled pipeline. The pressure waves in the water-filled pipeline travel at the speed of sound, making dynamic adjustments of the pressure with the vessel motion impractical.

Instead, it is important to anticipate the pressure extremes based on the sea-state and pressurise the pipeline accordingly. It is also recommended to hold on reeling operations if the sea-state leads to pressure extremes that would damage the liner.

SYMBOLS AND ABBREVIATIONS

ρ	Fluid Density *[kg/m^3]*
a	Acoustic Velocity *[m/s]*
Δu	Change in Fluid Velocity *[m/s]*
Δp	Change in Pressure *[Pa]*
L	Pipeline Length *[m]*
CCS	Carbon Capture and Storage
CRA	Corrosion Resistant Alloy
CS	Carbon Steel
FBE	Fusion Bonded Epoxy
IAWPS	International Association for the Properties of Water and Steam
MLP	Mechanically Lined Pipe

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