ORIGINAL ARTICLE

Numerical investigation on sealing performance of drainage pipeline inspection gauge crossing pipeline elbows

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Abstract
A pipeline inspection gauge (PIG) is routinely passed throughout the long-distance oil and gas pipelines by pipeline operators to clean the pipeline. Sealing performance is a significant evaluation index for PIG’s safety operation. To comprehensively evaluate the PIG’s seal performance, nonlinear finite element models were developed, and parametric analysis was conducted in this study. The accuracy of simulation model was validated from numerical and experimental results reported in the literature. The results show that comparing with the pigging in straight pipes, the sealing rubber cups of PIGs can be more easily detached from the pipe wall when passing through elbows, causing smaller sealing areas. For a typical elbow (with curvature radius equals to six times of pipe diameter) widely used in pipeline industry, the minimum sealing area of rubber cup is only 8.07% during common operation conditions. The sealing ability of rubber cups can be obviously enhanced by increasing the curvature radius for the pigging operation of small curvature elbow. Elbow radius slightly affects the cup’s sealing behavior when the curvature radius is over six times of pipe’s outer diameter. An increment in sealing cup interference can increase the contact area between cup and pipe wall, and the blockage risk of PIGs will be reduced due to the good sealing ability and sufficient driving force. The minimum interference required for the cups is 4% under a most common operation condition; that is, the sealing cup thickness, fluid pressure difference, and friction coefficient are 35 mm, 0.02 MPa, and 0.3, respectively. A proper decrease in sealing cup thickness will reduce the stiffness of rubber cups, indicating that the cups with a smaller thickness are more prone to deformation. Thus, an increase in differential pressure over PIG can enhance the sealing performance of cups when the cups are separated from pipe wall. A large friction coefficient is risky for a safe pigging due to the decrease in sealing region with the increase in friction coefficient. In engineering practice, proper measures should be taken to reduce friction force. Above all, the results obtained in this study provide a reference for the structural design of PIGs.

KEYWORDS
numerical investigation, parametric analysis, pipeline elbow, pipeline inspection gauge, sealing performance
1 | INTRODUCTION

As an effective pipeline maintenance equipment, the cup type pipeline inspection gauges (PIGs), as shown in Figure 1, are widely used in pipeline pigging. Catastrophic accidents may occur if insufficient driving force is provided on the drainage PIG during pigging. The traveling ability of PIGs can be enhanced by improving the sealing performance of cups, as better sealing behavior between the pipe and PIG can generate a larger differential pressure on the PIG.

For the safe operation of PIGs, numerous experimental and numerical studies have been conducted on the travel ability of PIG during pigging operation. Some studies focused on the fluid parameters and operation differential pressure. Soorgee reported a numerical study on the differential pressure needed for ball PIGs running in a pipe. Effects of material hardness, sphere PIG thickness ratio, and absolute pipeline internal diameter on differential pressure were analyzed. Mehdi et al. investigated the south pars sea line pigging using field test methods and numerical simulation. The optimization results of pigging flow rate were obtained. Chen et al. analyzed the movement characteristics of bypass PIGs. The features of pressure fluctuations during bypass pigging were proved. Chen et al. analyzed the movement characteristics of liquid water and gas condensate during bypass pigging.

For sealing performance and contact behavior of cup PIGs in pigging, such as contact stress and frictional force, valuable studies have been conducted by many researchers and pipeline operators. Dong et al. designed a bioinspired sealing disk, and the effects of interference, clamping rate, and webbed foot thickness on contact stress were analyzed. Zhu et al. studied the effects of sealing disk’s parameters on the contact force of a PIG, and some mitigating strategies were established to reduce the pigging risks. Hendrix et al. used experimental and numerical methods to analyze the friction force due to the sealing disks of a PIG. The required driving force and travel velocity of a PIG were predicted. Xue analyzed the effects of sealing cup thickness and hardness on PIG friction performance using a numerical simulation method. Liu et al. and Cao et al. studied the driving force for cup PIG based on the distribution of contact stress. The effect of interference and friction coefficient on sealing performance was studied using a numerical simulation method. Zhang et al. studied the friction and dynamic characteristics of a PIG passing through a girth weld. Shen conducted a series of studies on the friction behavior of rubber sealing cup material for PIGs. The relationship between moisture content of black powder and friction vibration characteristics of PIG was established. Chen and Liu numerically studied the effect of structural parameters of PIG on contact performance. Jiang et al. developed a three-dimensional (3D) numerical simulation model of pigging. The factors affecting the sealing performance of PIG crossing elbows were evaluated. A lot of relative studies are also reported for pigging, where the contact performance and stress response of rubber were studied.

Other studies paid more attention to the wear of rubber cup of PIGs. Zhang et al. evaluated the wear behavior of sealing disk in a dry pipe. The effect of different contact stresses between the rubbing pairs on the wear mode was evaluated. Shen et al. studied the friction and wear properties of nitrile rubber (NBR) against 316-L stainless steel pairs by using a sphere-on-disk test device.

These studies provide good references for the contact and sealing performance of rubber cups. The traveling ability can be evaluated based on the current research results. However, most numerical simulation studies are based on 2D model, and the key factors affecting the sealing performance of PIGs have been rarely studied. Few studies provide data for sealing performance evaluation when PIG is crossing a pipeline elbow. The cups may separate from the pipe wall, causing an insufficient driving force for the drainage PIG running in elbow.

In this study, a 3D numerical model was established to simulate the pigging of PIG crossing elbows with a curvature radius of 6D (D is the external diameter of pipeline). Based on the distribution of contact stress, the sealing performance of cups was quantitatively evaluated. Effects of some key parameters, that is, sealing cup interference, sealing cup thickness, friction coefficient between the cups and pipeline, and surface pressure difference of sealing cup, were evaluated. The research results can be referenced for the safety evaluation of pigging.

FIGURE 1 Drainage pipeline inspection gauge
2 | NUMERICAL SIMULATION METHOD FOR PIGGING OPERATION

2.1 | Geometric model of PIG and elbow

A geometric model of PIG was developed based on field investigation. The PIG is composed of a mandrel and four sealed cups. The size parameters of PIG geometric model can be obtained from the design drawings shown in Figure 2. The parameters of PIG and elbow are shown in Table 1. In this study, the value of cup interference can be calculated using the following equation:

\[ \delta = \frac{d_1 - d_2}{d_2} \times 100\% \]  

where \( \delta \) is the interference of sealing cups; \( d_1 \) is the diameter of sealing cups; \( d_2 \) is the inner diameter of pipeline.

2.2 | Material properties and behavior

The cups of PIG are made of rubber, which is one of the abrasion-resistant materials with a large deformation capability. Rubber materials are usually considered as hyperplastic materials. Material nonlinearity and geometric nonlinearity must be considered when establishing the constitutive model of rubber materials. Among several rubber material models, the two-parameter Mooney-Rivlin model was used, which can be described by the following equation:

\[ W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3) \]  

where \( W \) is the strain energy density function; \( C_{10} \) and \( C_{01} \) are Rivlin coefficient; \( I_1 \) and \( I_2 \) are Green invariants.

Existing studies have proved that Mooney-Rivlin model can better describe the nonlinear stress-strain behavior of rubber materials in numerical simulation. Zhang et al\(^{22}\) and Liu et al\(^{10}\) developed a FE model of pigging operation based on two-parameter Mooney-Rivlin model. The numerical analysis results were consistent with the experimental test results. Zheng et al\(^{23}\) studied the effect of key parameters on the sealing performance of HNBR packer. Mooney-Rivlin model was used in the FE model, satisfying the strain energy function well for the incompressible rubber material within a moderate strain range.

To obtain the parameters of rubber material model, a uniaxial tension test was performed in this study, as shown in Figure 3. According to the standard, the length of tensile specimen is 120 mm. Tensile tests of three groups of samples were conducted to reduce the effects of occasional factors. Strain loading was considered for test procedure. The stress-strain data of rubber materials can be obtained from the experimental data. The parameters of material model can be fitted using ABAQUS.\(^{24}\) The nonlinear stress-strain data obtained from uniaxial tension tests and fitted Mooney-Rivlin model are shown in Figure 4. A close match was observed between hyperelastic model curves and the experimental test data. The maximum relative error between them is 13%. The material of mandrel is 20# steel. Table 2 shows the material parameters used in the model.

2.3 | Numerical simulation model

A rigorous 3D nonlinear finite element model of the cup type PIG was established using a general finite element software ABAQUS v2016. Because the deformation of pipeline is much smaller than rubber cups, it was simulated using a discrete rigid body to improve the calculation efficiency, and the displacement was controlled by a reference point. The
eight-node brick elements with reduced integration (C3D8R) were used to simulate the PIG. The elbow was simulated using four-node bilinear rigid quadrilateral elements (R3D4).

A fine mesh with an element length of 0.007 m was used for contact area between rubber cup and pipe wall to evaluate the accurate sealing performance of cups in pigging, which has been verified to be fine enough to simulate the contact behavior. A coarse mesh with an element length of 0.015 m was used for the other parts of model. The used FE model consists of 126,562 elements. The numerical simulation model is shown in Figure 5.

Flange-bolt constraint was used to describe the interaction between cups and mandrel. The deformation of rubber cups occurs only in the lip of cup. Tie constraints are available for simulating the flange-bolt constraint mentioned above. Each node on slave surface is constrained to have the same motion as a point on the master surface. The tied area of tie is shown in blue in Figure 6. The interaction between rubber cups and pipe wall was simulated by using a surface-to-surface contact algorithm. The pressure over closure of normal behavior was considered as hard contact, and the penalty friction formulation was used to simulate the tangential behavior between contact pairs.

Boundary conditions were imposed on the established model as shown in Figure 7. The pipeline elbow was set as fully constrained. For pigging simulation and studying the contact behavior between cups and pipeline, the centreline of

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### TABLE 1  Geometry parameters of PIG and elbow

| Geometry parameters          | Value |
|------------------------------|-------|
| Diameter (sealing cups) \(d_1\) (mm) | 525   |
| Thickness (sealing cups) \(t_1\) (mm) | 35    |
| Inner diameter (pipeline) \(d_2\) (mm) | 508   |
| Wall thickness (pipeline) \(t_2\) (mm) | 6     |

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### FIGURE 3  Uniaxial tension test of cup material. (A) Test specimen. (B) Test procedure

### FIGURE 4  Uniaxial tension test data and fitted Mooney-Rivlin model

### FIGURE 5  Finite element model for PIG
elbow was divided equally into 30 parts. The PIG moves qua-
sistatically via 30 steps. A numerical analysis was performed
in three general stages. The contact between sealing cups and
pipe wall was established in the first stage. Fluid pressure was
applied to the external surfaces of cups in the second stage. In
the final stage, the moving displacement load along the pipe
elevator’s centreline was imposed on the reference point of PIG
to simulate its motion in elbow.

2.4 | Verification of proposed FE model

To verify the numerical simulation model developed in this
study, the existing numerical and experimental results were
compared with the proposed finite element results. The fric-
tion force was extracted and analyzed when the PIG entered
the straight pipeline. The variation curve plotted in Figure 8
indicates that the friction force between sealing cups and
pipe wall increases. The friction force is constant after the
contact relationships between each cup and pipeline were
established. The variation trends of these simulation results
shown in Figure 8 are consistent, and the maximum values

![FIGURE 6](image1)

![FIGURE 7](image2)

![FIGURE 8](image3)

**TABLE 3** Error results of FE model

| Moment (s) | Number of cups in contact with pipe wall | Numerical simulation results in this study (N) | Relative error (%) |
|------------|----------------------------------------|-----------------------------------------------|--------------------|
| 1          | 1                                      | 292.72                                        | 10.28              |
| 3          | 2                                      | 611.30                                        | 10.76              |
| 4          | 3                                      | 907.08                                        | 8.01               |
| 5.3        | 4                                      | 1265.35                                       | 2.39               |
| 6.5        | 4                                      | 1244.53                                       | 3.56               |
of friction force are close. The relative error between the two results shown in the following figure varies from 2.39% to 10.76%. The relative errors of finite element calculation results at some key moments are shown in Table 3. There is a good agreement between the two sets of results. Generally, the FE model proposed in this study was validated to be suitable for simulation analysis.

3 | SEALING PERFORMANCE ANALYSIS FOR PIG CROSSING ELBOW

The motion of drainage PIG in pigging operation is usually driven by the differential pressure. A poor sealing performance can be readily caused by the detachment between cups and steel pipeline, which will lead to a high risk of blockage, especially when the PIGs are running in the elbow. As shown in Figure 9, the pressure relief region due to the separation of sealing cup and pipe wall can be clearly observed. It can be easily observed that the rubber cup has better sealing performance when the PIG is running in a straight pipeline.

In this study, the sealing performance of PIG can be acquired based on the contact stress between rubber cups and pipeline when the PIGs are crossing the pipeline elbow. Considering the influence of pressure difference in fluid during pigging process, variable pressure loads are applied on the inner surface of the sealing cups, the PIG skeleton, and the anticollision head plate according to the difference in simulation conditions. Pressure difference in baseline condition is 0.02 MPa. The sealing cup interference was 2%, which can be calculated by the outer diameter of sealing cups and the inner diameter of pipeline as shown in formula 1. The friction coefficient was 0.3 for cups and pipe wall. According to the previous studies, the 0.3 coefficient can approximately simulate the friction contact conditions of common pigging processes. To characterize the magnitude and distribution of contact stress, each sealing cup was divided into four regions, as shown in Figure 10. The Abaqus Standard was used in this study, as the pigging process of PIG can be regarded as quasistatic process. The results of contact stress in four directions of rubber cups can be well extracted and analyzed.

For each region, the sealing performance can be indicated by the ratio of sealing zone area and contact zone area. Figure 11 shows the variation curve of the percentage of sealing area of each region in four cups vs time. Region 1 and region 4 of the behind cup have poor sealing performance. The minimum percentage of sealing area is 8.07%. Pressure relief will occur easily during pigging. The other cups maintain better sealing performance when the PIG is crossing elbows; that is, a safe and efficient pigging operation will depend on...
the sealing behavior of behind cup, which was selected for contact stress evaluation.

As the percentage of sealing region is relatively small within 5-20 seconds, a moment at 10 seconds was selected. At this moment, the contact stress distribution of cups was studied. The contact stress of each node on the path along the axial direction of the cup, as shown in Figure 12, was analyzed. The maximum contact stress on the path was selected to evaluate the sealing performance of cups in this direction. Then, the maximum contact stress along the circumference of cups can be obtained.

Figure 13 shows the curve of maximum contact stress along the circumferential direction of the behind cup. The contact stress shows a nonuniform distribution along the circumference of behind cup. The contact stresses in regions I
The maximum and minimum values of contact stress are 0.38 MPa and 0 MPa, respectively. A pressure relief region exists in the rubber cup because the contact stress is less than fluid pressure. Fluctuation of results can be attributed to the fact that the contact stresses are derived from discrete nodal outputs, which can be mitigated by increasing the number of elements.

### PARAMETRIC ANALYSIS

#### 4.1 Parameter range in the investigation

A series of parametric analysis was performed based on the proposed numerical simulation model to evaluate the effects of main factors, for example, the sealing cup interference, sealing cup thickness, friction coefficient, and differential pressure, on the sealing performance of cups. Based on the design drawings and field investigation, the range of common design parameters of PIG is determined which can meet the engineering requirements. The parameters of each group are shown in Table 4.

#### 4.2 Effects of sealing cup interference

Sealing cup interference is one of the significant geometric parameters of cups. A proper sealing cup interference can ensure the pigging ability of PIGs. Effects of sealing cup interference on the sealing performance of PIG are described in this section. The value of cup interference varies from 2% to 5%. The contact stress contours of behind cup with different interferences are shown in Figure 14. The sealing area increases significantly as the cup interference increases. The behind cup will maintain good sealing behavior when the sealing cup interference is greater than 3%. The plots in Figure 15 show that the maximum contact stress distribution along the conferential direction of behind cup. The contact stress increases with increasing sealing cup interference. Figure 16 shows the percentage of sealing area of each cup vs the sealing cup interference. Similar to the trend shown in

| Group | Sealing cup interference (%) | Sealing cup thickness (mm) | Friction coefficient | Differential pressure (MPa) | Elbow curvature radius |
|-------|-------------------------------|---------------------------|---------------------|----------------------------|----------------------|
| 1     | 2; 3; 4; 5                    | 35                        | 0.3                 | 0.02                       | 6D                   |
| 2     | 2                             | 5; 15; 25; 35             | 0.3                 | 0.02                       | 6D                   |
| 3     | 2                             | 35                        | 0.3; 0.2; 0.3; 0.4; 0.5 | 0.02                       | 6D                   |
| 4     | 2                             | 35                        | 0.3                 | 0.02; 0.04; 0.06; 0.08     | 6D                   |
| 5     | 2                             | 35                        | 0.3                 | 0.02                       | 2D; 6D; 8D; 10D      |

**FIGURE 13** Maximum contact stress distribution along the conferential direction of behind cup and radial sketch of sealing cup

**TABLE 4** Parameter range of sealing performance evaluation
Figure 14, the percentage of sealing area for cup behind increases from 26.6% to 30.5%, when sealing cup interference increases from 2% to 5%.

4.3 | Effects of sealing cup thickness

Sealing cup thickness is another common design parameter of PIGs. An increase in rubber cup thickness will increase the effective cleaning distance. However, more attention should be paid to a higher risk of blockage due to cup thickness increase. To characterize the effect of sealing cup thickness, four thickness values, 5, 15, 25, and 35 mm, were considered in the numerical simulation. The contact stress contours of behind cup at different sealing cup thicknesses are plotted in Figure 17. The behind cup has better sealing behavior when the cup thickness is 5 mm. Figure 18 shows plots of the contact stress along the circumferential direction of behind cup. The change trend of contact stress on rubber cups is similar under different sealing thicknesses. The pressure relief phenomenon will occur on the surface of cups. The bending stiffness of sealing cups is decreased with the decrement of sealing cup thickness which is favorable to the establishment of contact between sealing cup and the inner wall of elbow.

Figure 19 shows the results of parametric analysis of various cup thicknesses. The percentage of sealing area for cups first decreased and then increased with increasing sealing cup thickness. The percentage of sealing area dramatically decreased when the cup thickness varied from 5 mm to 15 mm. Some useful conclusions can be obtained based on the curve plotted in Figure 19. For the front cup and behind cup, the sealing performance is weakened when the thickness of cup is 25 mm, while cup middle 1 and cup middle 2 have poor sealing performance when the cup thickness is 15 mm.

4.4 | Effects of friction coefficient

Existing studies have proved that different media in pipelines will vary the friction coefficient between sealing cups and pipe wall, and different friction conditions will affect the safety of pigging operation. To quantitatively evaluate the effect of friction conditions on the sealing performance of PIGs, four friction coefficients, that is, 0.1, 0.2, 0.3, 0.4, and 0.5, were selected in the FE model. The variation range of friction coefficient mentioned above can better describe the friction condition, which is affected by numerous factors. The contact stress contours of sealing the behind cup at different friction coefficients are shown in Figure 20. The friction coefficient clearly affects the sealing performance of PIG. The sealing area decreases with increasing friction coefficient. Previous studies show that the contact stress between sealing cups and pipe wall decreases with increasing friction coefficient. Increasing the roughness of the pipe inner wall is unfavorable to the contact behavior of PIG.

PIG has poor sealing performance, because the maximum contact stress distribution along the conferential direction of behind cup as plotted in Figure 21 increases with the increase in friction coefficient. The risk of blockage will increase significantly when pigging operation was carried out under a higher friction coefficient. As shown in Figure 22, the variation in the sealing area percentage of other cups with friction coefficient is similar to that of behind cup. To ensure the safety of pigging, the effect of friction coefficients cannot be ignored. Reasonable measures should be taken to reduce the friction between sealing cups and pipe wall.

4.5 | Effects of differential pressure

One of the most significant parameters that must be considered for a pigging operation is fluid pressure difference. The driving force and cleaning performance of PIGs are influenced by pressure difference. The effects of differential pressure on the sealing performance of cups are described in this section. Four differential pressures were investigated, namely, 0.02 MPa, 0.04 MPa, 0.06 MPa, and 0.08 MPa. The corresponding variation in the maximum contact stress along the circumferential direction of behind cup is shown in Figure 23. As expected, an increase in the differential pressure leads to an increase in the maximum contact stress.

From the contact stress contours of sealing the behind cup shown in Figure 24, it can be observed that pressure relief will occur when the differential pressure is 0.02 MPa. The behind cup has a better sealing performance when the differential pressure is 0.04 MPa. Figure 25 shows that the percentage of sealing area for rubber cup first decreased and then increased with the increase in differential pressure when no pressure relief occurs. Otherwise, the trend is contrary to
that mentioned above. This is because an increase in differential pressure will increase the contact area between the cup and pipe wall. Especially when pressure relief occurs in cups, increasing the pressure difference can improve the sealing performance of cups significantly. On the other hand, an increase in fluid pressure difference will also increase the sealing critical pressure.

4.6 Effects of elbow curvature radius

The pigging may be performed in elbows with various curvature radii. To study the effects of elbow curvature radius on cup sealing performance and conduct the safety evaluation for drainage PIGs when pigging was carried out in a small curvature radius elbow, parametric analyses were carried out for four different elbow curvature radii, $r = 2D, 6D, 8D,$ and $10D$. Figure 26 shows the contact stress distribution contours of sealing the behind cup vs different curvature radii. As expected, the pressure relief area of PIGs running in a small curvature elbow increased. The sealing performance of behind cup can be enhanced with the increase in curvature radius, when PIG is operated in the pipeline elbow with a curvature radius of less than $8D$. Otherwise, the curvature radius of elbow slightly affects the sealing ability.

The variation curves plotted in Figure 27 indicate that the percentage of sealing area for the behind cup varies from 25.4% to 28.3% when the elbow radius increases from $2D$ to $8D$, while the sealing area percentage increases by only 0.1% when the elbow radius varies from $8D$ to $10D$. This is because of an obvious deviation between the operation trajectory of PIG and the centreline of elbow, causing a detachment between the rubber cup and pipe wall more likely to occur.
Figure 28 shows that the contact stress in the local region of sealing cups increases significantly when the curvature radius decreases from $10D$ to $2D$, while the contact area is significantly reduced.

5 | CONCLUSIONS

Sealing performance plays a significant role in pigging. An insufficient driving force due to pressure relief increases the risk of blockage. To evaluate the sealing performance of cups based on the distribution of contact stress, a rigorous 3D non-linear numerical simulation model was established in this study. A nonlinear stress-strain relationship of rubber materials was considered by performing a uniaxial tension test. The FE model developed in this study was verified. The maximum relative error is 10.76%. Parametric analysis was also performed to evaluate the effect of sealing cup interference, sealing cup thickness, friction coefficient, differential pressure over PIG, and elbow curvature radius on the sealing performance of cups. Based on the numerical simulation results, some conclusions can be drawn as follows:

1. The blocking failure of PIGs occurs due to the insufficient driving force caused by the separation of sealing cups and pipe wall when pigging operations are conducted in a small curvature radius elbow. The percentage of sealing area of rubber in the behind cup is only 8.07% during common operation in a typical type of elbow with a curvature radius of $6D$.

2. The contact stress of rubber cups can be better utilized for sealing behavior evaluation. The interference of sealing cups has a significant effect on the distribution of contact stress. When sealing cup interference varies from 2% to 5%, the percentage of sealing area for the behind cup increases from 26.6% to 30.5%. The minimum interference required for cup sealing is 4% for the following operation conditions: sealing cup thickness, fluid pressure difference, and friction coefficient of 35 mm, 0.02 MPa, and 0.3, respectively.

3. When the rubber cups of PIGs are separated from pipe wall, properly decreasing the sealing cup thickness or increasing the differential pressure can eliminate the pressure relief region of cups. The minimum fluid pressure difference required for cup sealing is 0.04 MPa when the sealing up interference, sealing cup thickness, and friction coefficient are 2%, 35 mm, and 0.3, respectively.

4. For pigging process safety, the frictional force should be reduced. When the friction coefficient varies from 0.1 to 0.5, the percentage of sealing area for the behind cup decreases from 31.4% to 23.7%.

5. The blockage risk of pigging operation in a small curvature radius elbow is significantly increased. For the pigging of
a small elbow radius, the curvature radius clearly affects the sealing behavior. Otherwise, the effect can be ignored. The percentage of sealing area for the behind cup varies
from 25.4% to 28.3% when the elbow radius increases from 2D to 8D, while the sealing area percentage increases by only 0.1% when the elbow radius varies from 8D to 10D.

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