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In the ITER, the neutrons created by D-T reactions activate structural materials, and thereby, the circumstance in the vacuum vessel is under intense gamma radiation field. Thus, the in-vessel components such as blanket are handled and replaced by remote handling equipment. The objective of this report is to study the compactness of the remote handling equipment (a vehicle/manipulator) for the ITER blanket maintenance. In order to avoid the interferences between the blanket and the equipment during blanket replacement in the restricted vacuum vessel, a compact design of the equipment is required. Therefore, the compact design is performed, including kinematic analyses aiming at the reduction of the sizes of the vehicle equipped with a manipulator handling the blanket and the rail for the vehicle traveling in the vacuum vessel. Major results are as follows:

1. The compact vehicle/manipulator is designed concentrating on the reduction of the rail size and simplification of the guide roller mechanism as well as the reduction of the gear diameter for vehicle rotation around the rail. Height of the rail is reduced from 500 mm to 400 mm by a parameter survey for weight, stiffness and stress of the rail. The roller mechanism is divided into two simple functional mechanisms composed of rollers and a pad, that is, the rollers support relatively light loads during rail deployment and vehicle traveling while a pad supports heavy loads during blanket replacement. Regarding the rotation mechanism, the double helical gear is adopted, because it has higher contact ratio than the normal spur gear and consequently can transfer higher force. The smaller double helical gear, 996 mm in diameter, can achieve 26% higher output torque, 123.5 kN•m, than that of the original spur gear of 1,460 mm in diameter, 98 kN•m. As a result, the manipulator becomes about 30% lighter, 8 tons, than the original weight, 11.2 tons.
2. Based on the compact design of the vehicle/manipulator, the structural analysis for the rail and the kinematical analysis for replacement of blanket are also performed. It is confirmed that every blanket can be replaced without any interferences in the vessel.

Keywords: ITER, Fusion, Tokamak, Blanket, Remote Maintenance, Compact Design, Vehicle/Manipulator

ITER ブランケット遠隔保守機器の小型化設計

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国際熱核融合実験炉(ITER)では、DT 反応によって生じる中性子が構造物を放射化するため、真空容器内は高γ線環境下にある。したがって、ブランケット等の真空容器内機器の保守は遠隔機器によって実施される。本報告書では、ITER ブランケット遠隔保守機器（ビークル／レール式マニピュレータ）の小型化について述べる。真空容器内でのブランケットの交換保守時におけるブランケットと遠隔保守機器との干渉を回避するためには、遠隔保守機器の小型化が必要となる。このため、マニピュレータが搭載されたビークルおよびビークルが真空容器内を走行するためのレールの断面形状の寸法縮減を目的に、機構解析を含めて小型化設計を実施した。

主な結論は以下の通り。

1．レール断面形状の小型化、ビークル走行機構の単純化、回転機構用歯車の小径化、の 3 点に着目して小型化設計を行った。レール断面については、レール重量、剛性、応力についてパラメータサーベイを行い、レール高さを 500mm から 400mm に低減することができた。ビークル走行機構に関しては、レール展開時や走行時等、負荷が比較的低い場合にはローラで支持し、ブランケット交換時のような大負荷を支持する場合にはパッドで支持するという、走行・支持の機能を分離してローラとパッドで分担する機構を考案し、小型化に成功した。回転機構用歯車に関しては、従来使用していた「平歯車」よりもかみ合い率が大きく、伝達力が高くなる「やまば歯車」を採用し、より高トルクを許容可能な機構とした。これにより、歯車径を 1,460 mm から 996 mm に減少させたにもかかわらず、機構自体の出力トルクは 98 kN•m から 123.5 kN•m へと 26%向上した。これらの小型化設計の結果、マニピュレータは 11.2 トンから 8 トンにまで約 30%軽量化された。

2．ビークル／レール式マニピュレータの小型化設計に基づいてレールの構造解析およびブランケット交換時の機構解析を行い、ブランケットが干渉なく交換できることを確認した。

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1. INTRODUCTION

1.1 Background

The maintenance of in-vessel components can be accomplished by removing a failed component and replacing it by a new one or re-installing the component after repair or refurbishment in the hot cell. Due to neutron activation, repair, inspection or maintenance of ITER in-vessel components has to be carried out remotely [1]. The shield blanket is a RH class 2 in-vessel component composed of 421 modules[2),3)]. Replacement of some failed shield blanket modules may be required a few times during the lifetime of ITER due to local erosion or defects, including leaks, and the complete exchange of the shield blanket modules with breeding blanket modules may be needed once during the ITER lifetime. During maintenance, monitoring by an in-vessel viewing system is also required.

Each blanket module is equipped with ten remote handling access holes through its plasma-facing first wall. Four holes allow access for the tool that bolts and unbolts the flexible supports, four give access for welding, cutting and inspection of the cooling pipes and for bolting and unbolting of the electrical straps, and two are used to grasp the module and hold it securely during handing into and out of the VV. Module transporters, mounted at intermediate ports, are used to load modules into casks, thereby enabling the modules to be shuttled to and from the hot cell. ITER blanket maintenance strategy has been confirmed as feasible by a comprehensive design, research and development program during Engineering Design Activity [4] (EDA).

This report shows a continuation of the systematic design and R&D[5)-7)] started during EDA.

1.2 Objectives

The objective of this report is to study a compact design of the remote handling equipment for blanket of the ITER. In order to increase the accessibility for blanket maintenance in the VV, the compact design of vehicle manipulator is performed by considering the reduction of the sizes of rail and vehicle structures. The kinematic analyses and review of load and design conditions are also included in the report in order to assess the feasibility of the modified design

The report includes the following items to study the remote handling scenario and design.

- Review of the blanket maintenance scenario, including the details of blanket interfaces such as gripping configuration, key configuration and cooling pipe configuration.
- The compact design of vehicle/manipulator will be performed by considering the reduction of the sizes of rail and vehicle structures.
- Kinematic CAD analysis for blanket module replacement in the VV.

- Update and review of load and design conditions, such as moment, torque and surface pressure on the gear, acted on the rail and rotating mechanism during blanket replacement in order to assess the feasibility of the modified design.

2. REVIEW OF THE BLANKET MAINTENANCE SCENARIO

2.1 Latest Design of Blanket Maintenance System

The vehicle/manipulator had been introduced and designed for blanket maintenance during EDA. **Figure 2-1** shows its poroidal section in the Final Design Report (FDR) published in July 2001. The blanket maintenance scenario was reviewed referring this design. Main parameters regarding the review were as follows:

- radius of rail: 6,100 mm
- rail size of poroidal section: 500 mm in height, 250 mm in width
- offset between rail center and manipulator center: 1,130 mm
- pitch circle diameter of sector gear: 1,460 mm.

2.2 Result of Review

Major results of the review were summarized as follows:

- The No. 9 blanket module interferes with the end-effector as shown in **Fig. 2-2**. The end-effector must be more compact.
- Most of modules other than No. 9 do not interfere with the end-effector during removing and installing operation, however, some of them must be interfere during welding or cutting operation because the welding/cutting tool requires additional space. **Figure 2-3** shows replacement of the No. 12 module. The gap is already narrow between the manipulator and the first wall.
- During transfer of the module, the manipulator must be rotated not only around the rail but also along it, and thus, the minimum gap to the first wall is very narrow.
- The manipulator interferes with the vehicle during replacement of the No. 4 module as shown in **Fig. 2-4**.
- The No. 7, 8, 9, and 18 module cannot be replaced independently. Replacement of theses modules needs prior removal of the adjacent modules as shown in **Figs. 2-5~8**.
- The direction of replacement is not parallel to the axis of cooling. Precise alignment of the pipes before welding becomes difficult because of this arrangement.
- The axes of flexible bolts are not aligned to the same. Therefore, the bolting tool needs four degrees of freedom (two for translation and two for rotation). If the axes are aligned to the same direction, two rotational degrees of freedom can be reduced and the mechanism of the tool can be simplified.

Among the above issues, the former four can be solved by a more compact manipulator, while the latter three issues must be solved by redesign of the blanket. The **Section 3** mentions a compact design of the vehicle/manipulator reducing the rail size in poroidal section and the pitch circle diameter of the sector gear mainly.

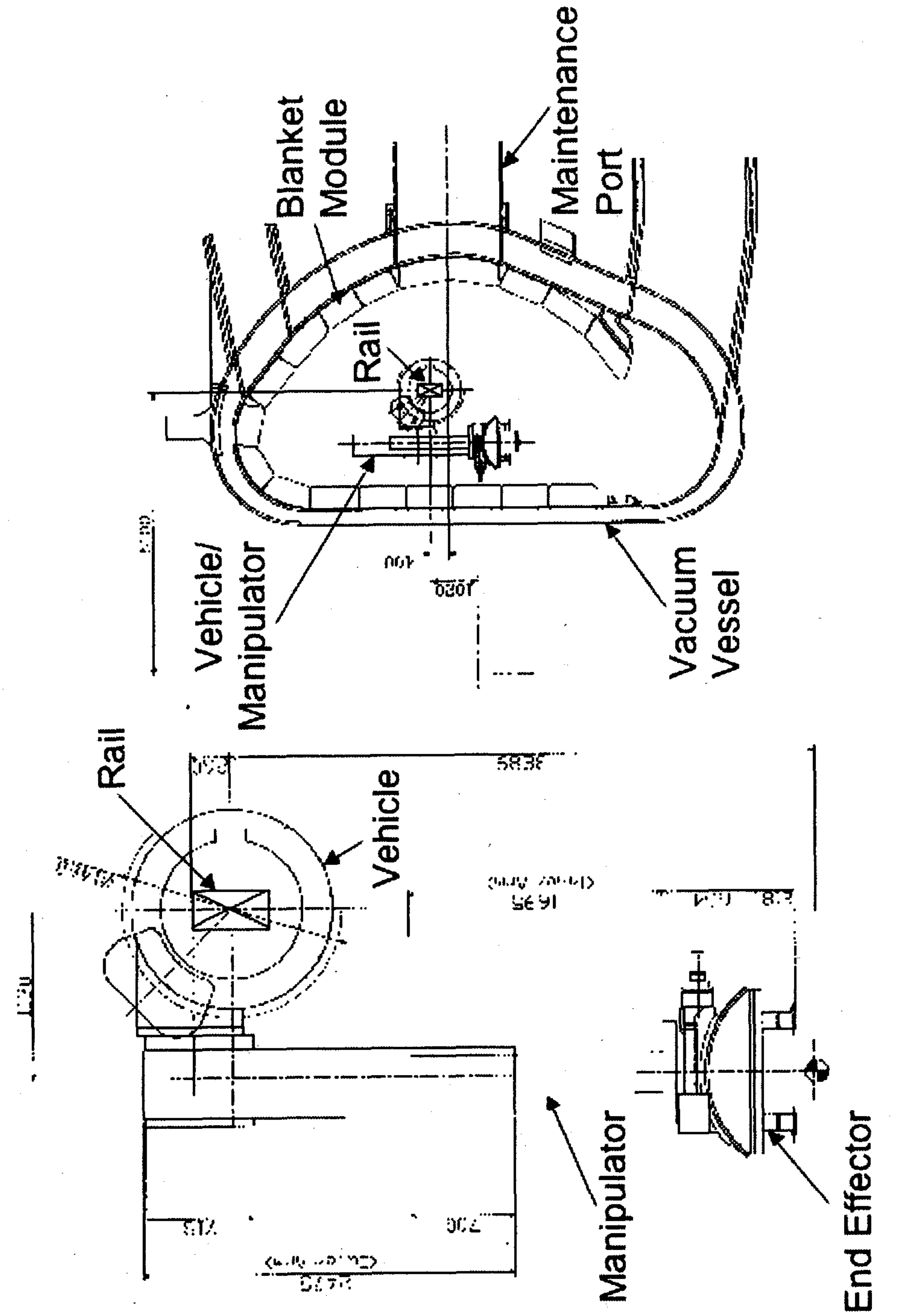


Fig. 2-1 Poroidal Section of Vehicle/Manipulator

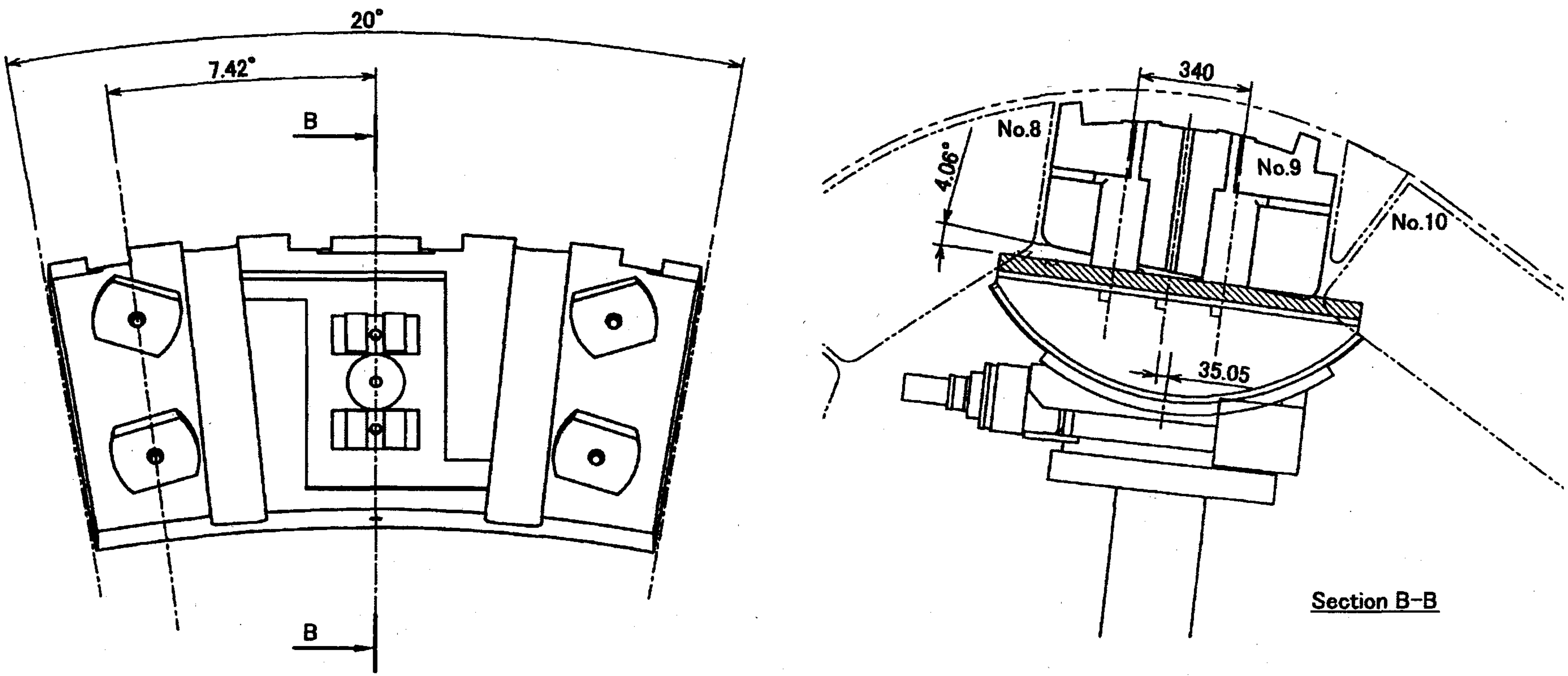


Fig. 2-2 Interference Check between End-Effector Base and No. 9 Module

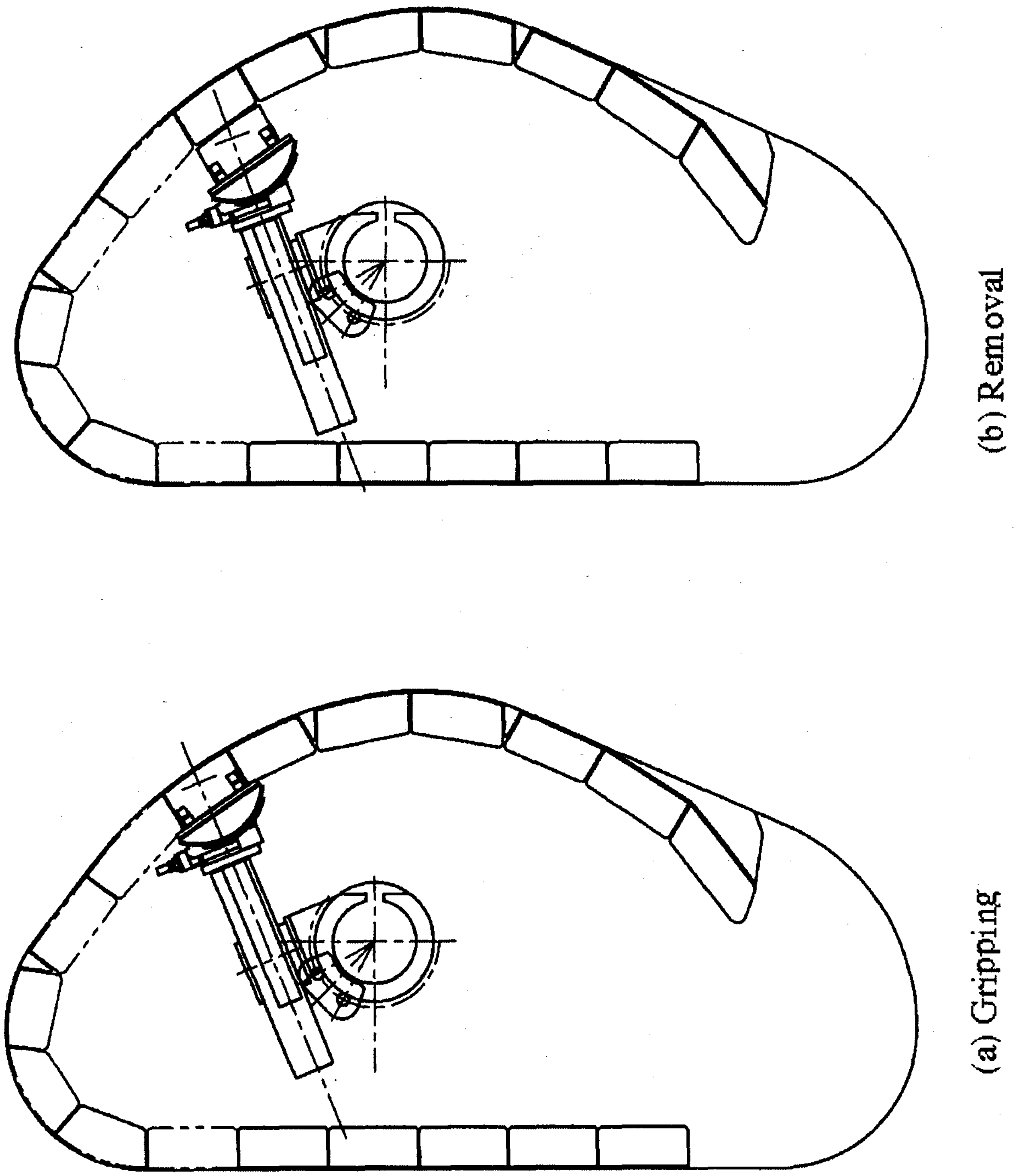
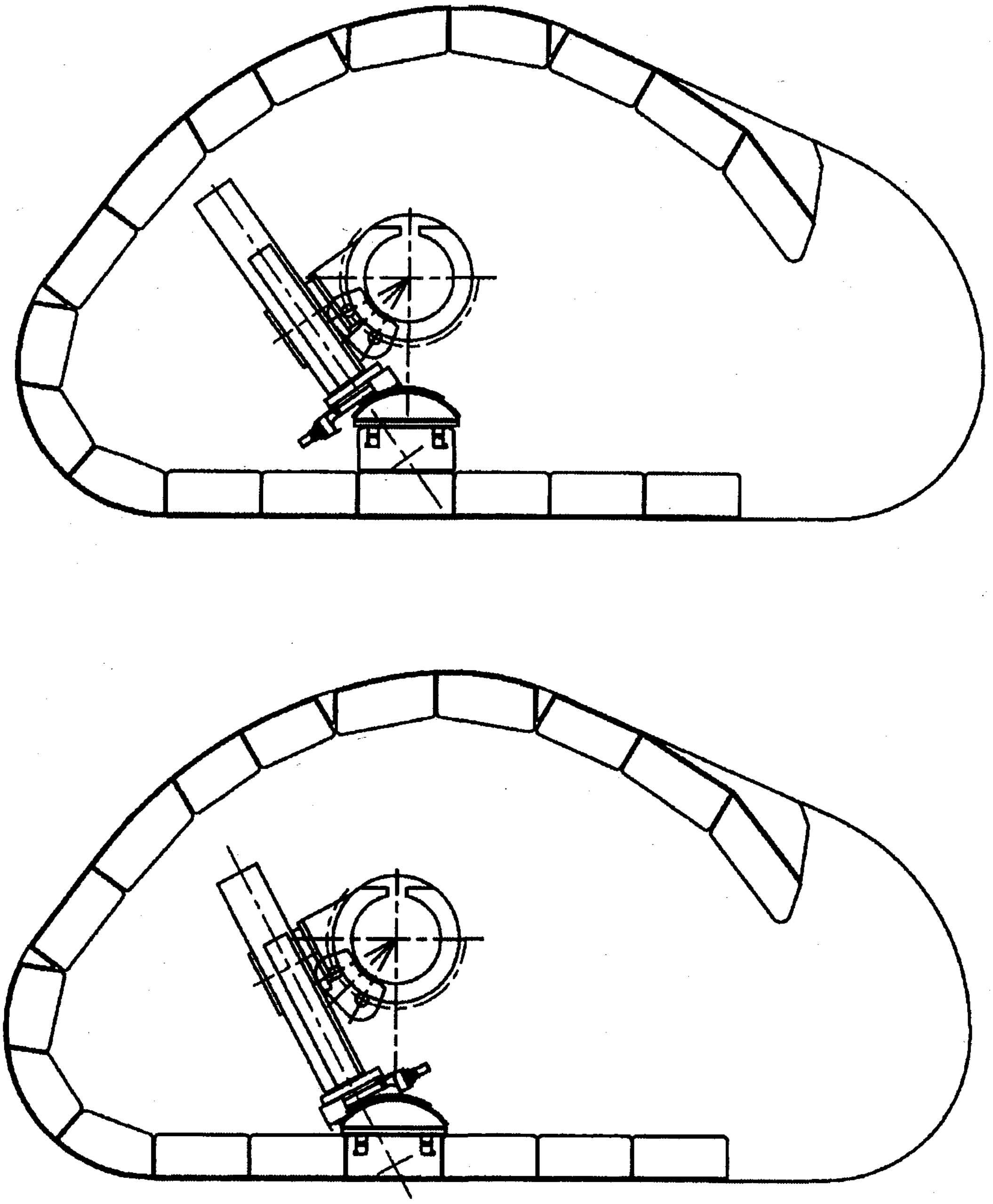


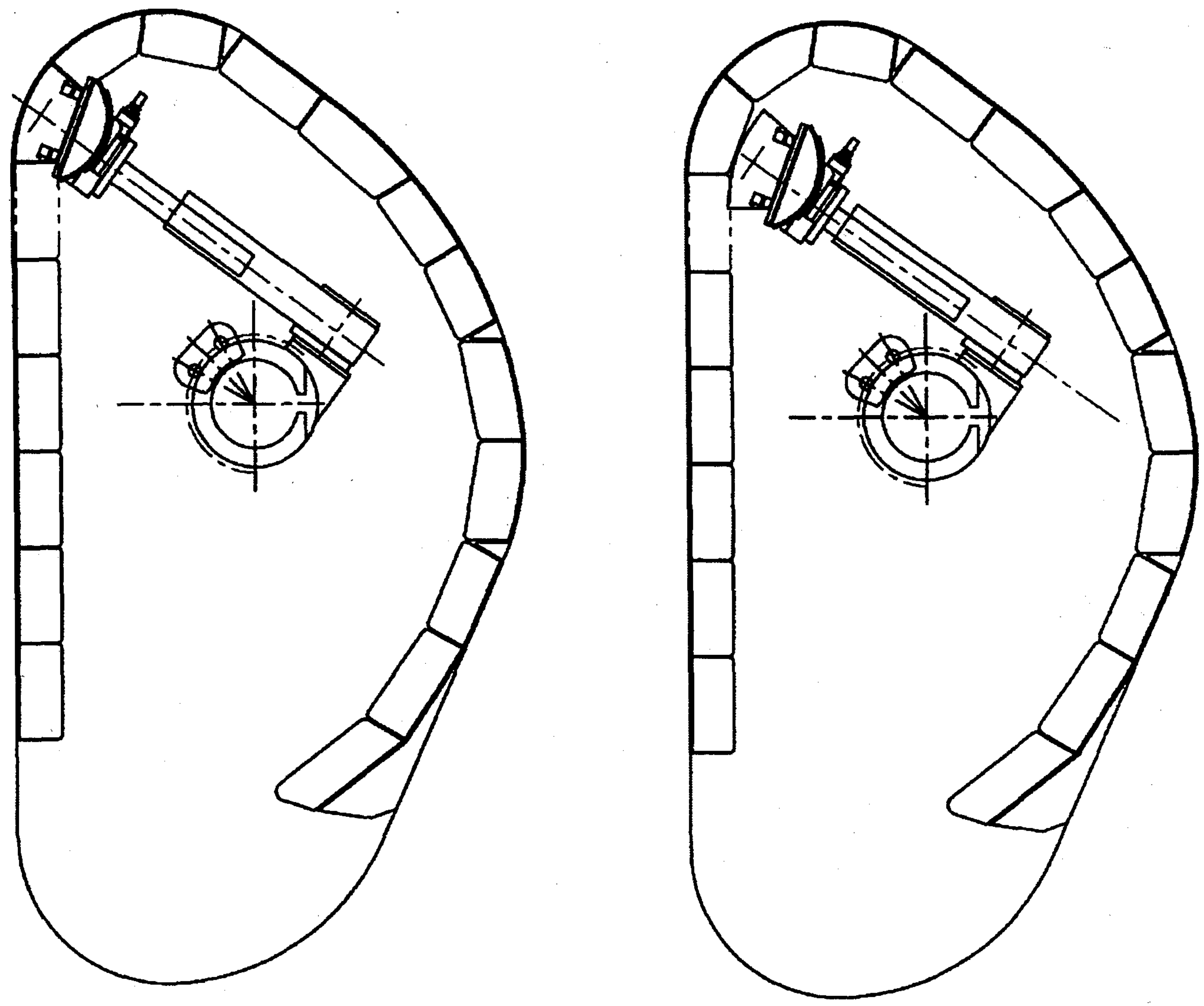
Fig. 2-3 Replacement of No. 12 Module



(a) Gripping

(b) Removal

Fig. 2-4 Replacement of No. 4 Module



(a) Gripping

(b) Removal

Fig. 2-5 Replacement of No. 7 Module

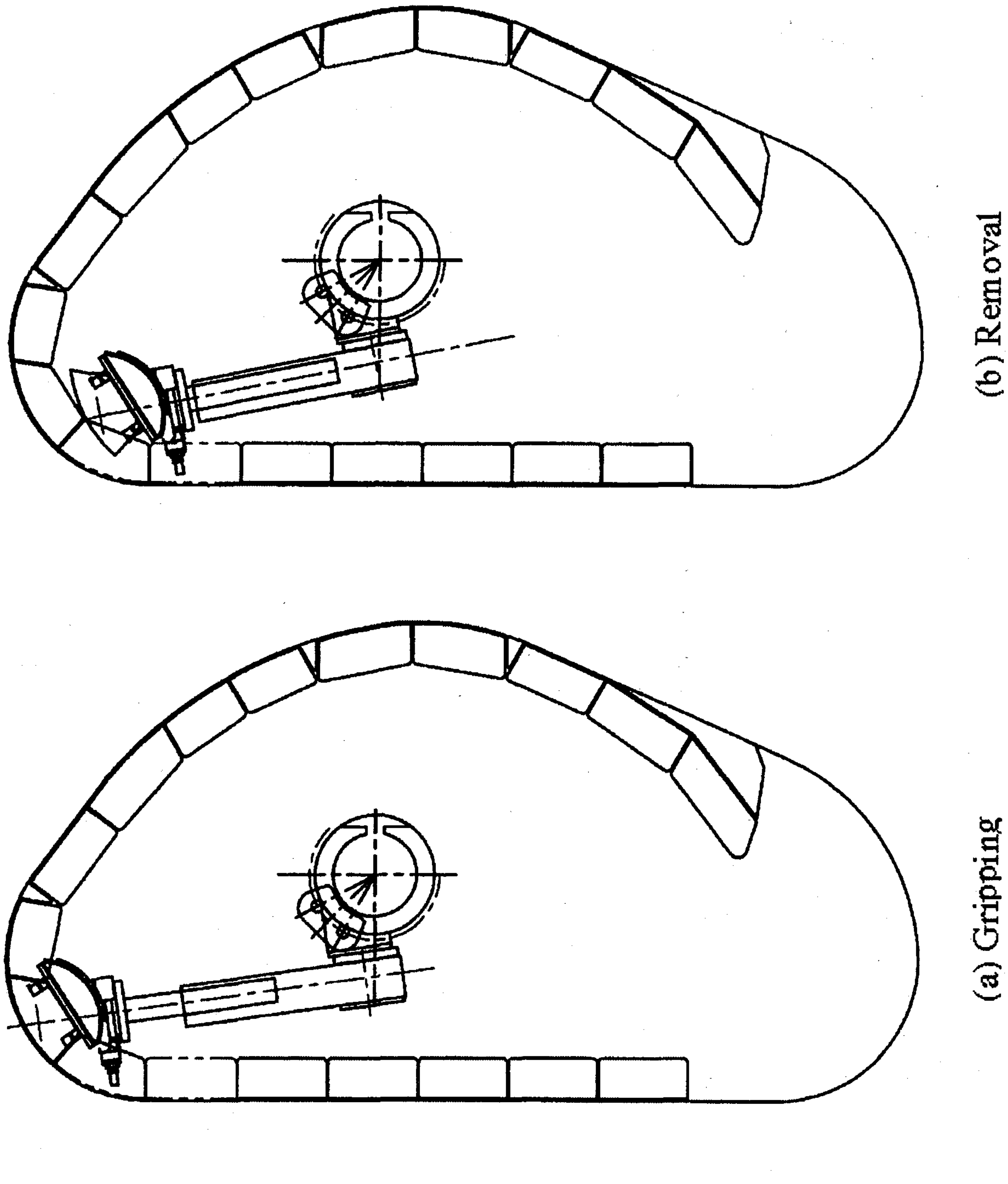
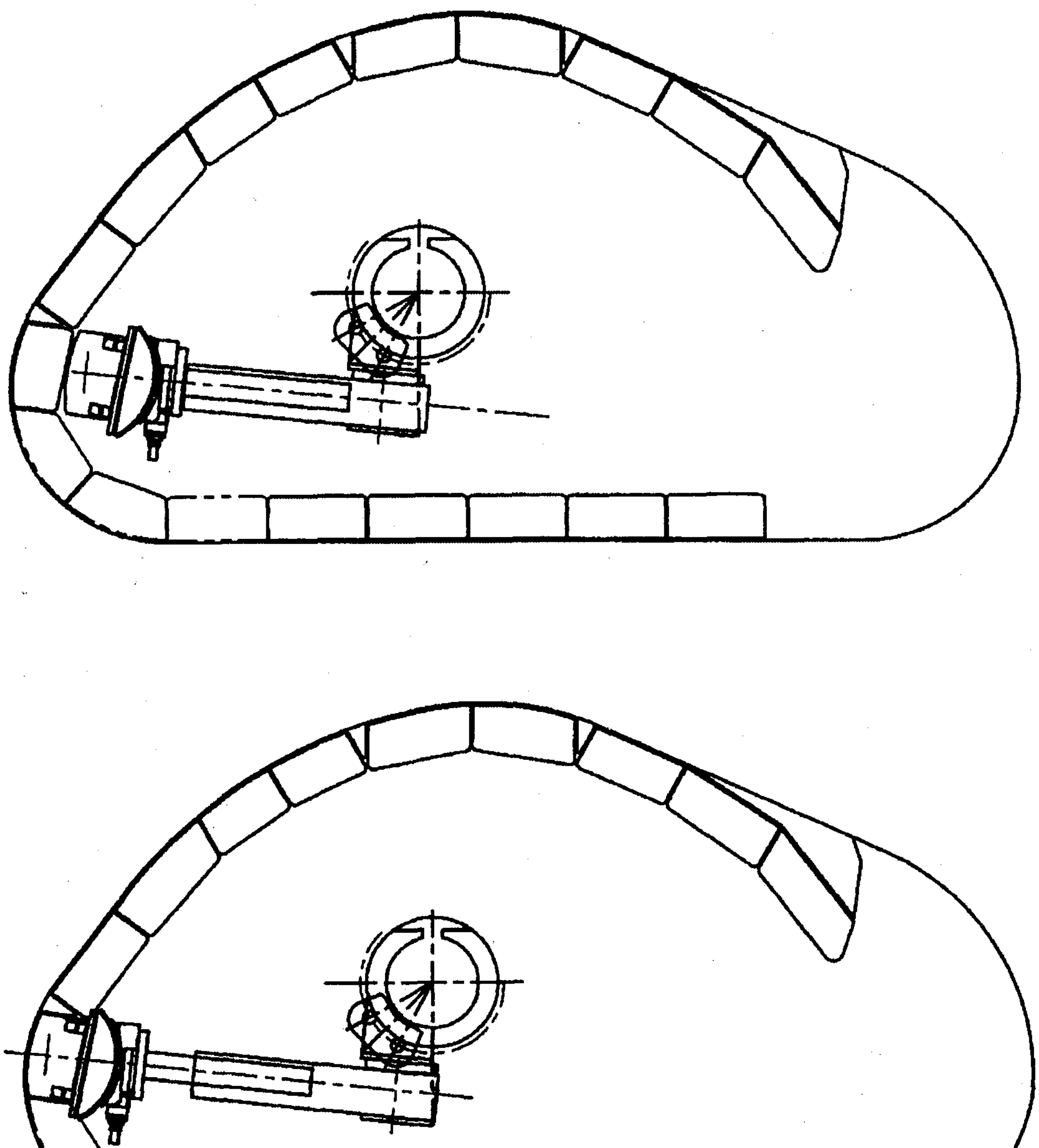


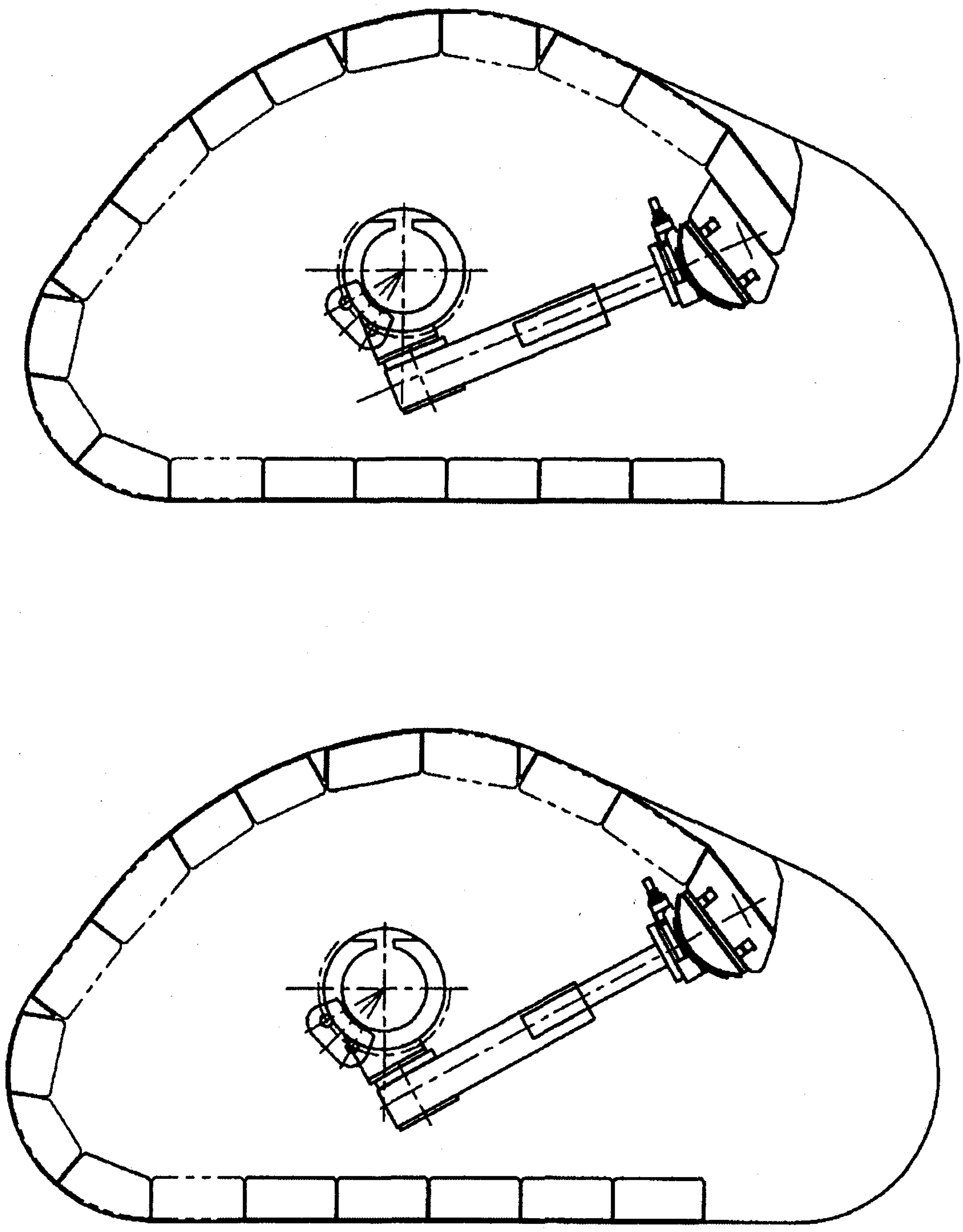
Fig. 2-6 Replacement of No. 8 Module



(a) Gripping

(b) Removal

Fig. 2-7 Replacement of No. 9 Module



(b) Removal

(a) Gripping

Fig. 2-8 Replacement of No. 18 Module

3. COMPACT DESIGN OF VEHICLE/MANIPULATOR

3.1 Key Components for Compact Design

Figure 3-1 compares cross sections of the vehicle/manipulators in the FDRs published in 1998 and 2001. The size of the manipulator including the end effector had been reduced already until 2001. However, the vehicle and the rail are almost as large as they were in EDA. Therefore, this report concentrates on the compact design of them. The key components for the design are as follows:

- Rail including joint
- Guide roller
- Sector gear

3.2 Design of Rail and Guide Roller

As the first step, reduction of the rail size is investigated. The rail is supported by guide rollers during deployment. Once the rail is deployed, on the other hand, the vehicle with rollers is supported by the rail during replacement of the module and movement. The lengths of the rollers are limited by the rail size, and thus, the smaller the rail becomes, the higher the Hertz's stresses induced by the rollers rise. This report tries two approaches to reduce the size of the rail. One approach is reduction of load by separation of function. **Figure 3-2** shows a guide roller mechanism with a pad. When the load is relatively light, the rollers contact directly with the rail as shown in **Figure 3-2(a)**. If a heavy load is applied, a spring mechanism is activated as shown in **Figure 3-2(b)** and the load is supported by the pad whose wide bottom enables to sustain. The function of the guide roller mechanism is separated by this concept and the load is shared by the rollers and the pad: the rollers support relatively light loads during rail deployment and vehicle movement while a pad supports heavy loads during module replacement. Thereby, the load condition for the roller is drastically reduced. The other approach is adoption of a stronger material. The rail was made of SM490 (rolled steels for welded structure, defined in JIS G 3106) in the EDA from the viewpoint of manufacture. By recent progress of technology, usage of SM570, a stronger material than SM490, becomes feasible.

Table 3-1 shows a parameter survey of the rail size considering the Hertz's stress by the guide rollers. The rail radius is increased by 50 mm to reduce the torsion moment. The load condition is decided considering following two phases:

- Rail deployment phase: the rollers support a part of the rail (105 degrees in maximum).
- Operation phase: the rollers support a manipulator (104.9 kN, temporary value from preliminary study) and a module (45.5 kN).

Figure 3-3 shows the load condition of the rail deployment phase. Regarding the top rollers, the load of the operation phase is larger than that of the rail deployment phase, while it is contrary for the inner/outer rollers.

As a result, the height of the rail is reduced to 400 mm. The proposed design of the rail can be summarized as follows:

- Poroidal cross section: 400 mm in height, 250 mm in width
- Wall and rib thicknesses: 10 mm and 6 mm, respectively
- Material: SM570 (rolled steels for welded structure, defined in JIS G 3106)

- Allowable Hertz's stress: 874 MPa (=1.9σ_y=1.9•460, according to MITI Notification No. 501)
- Maximum Hertz's stress: 794.4 MPa

As the next step, a detailed structural analysis for the proposed design is performed considering the operation phase where one vehicle with manipulator stays at the middle of two rail supports (45 degrees from them) with gripping the module. The analysis condition is as follows:
- Angle of rail: 90 degrees
- Rail weight: uniformly distributed
- Vehicles (104.9 kN) and module (45.5 kN): concentrated on the center (45 degrees)
- Moment around the rail: 98 kN•m

Figure 3-4 shows the analysis model of the rail, which simulates 45 degrees considering symmetry. As shown in **Fig. 3-5**, all the degrees of freedom are fixed at the supported end while only the axial direction (z direction) is fixed on the symmetric surface.

The results are shown in **Figs. 3-6~3-8**. As shown in **Fig. 3-6**, the maximum displacement of the rail is 19.4 mm. The maximum Mises stress is 267 MPa at the supported end including peak stress as shown in **Figs. 3-7~3-8**. It is lower than the allowable stress, 307 MPa (=σ_y/1.5=460/1.5).

The articulation of the rail is also redesigned reflecting reduction of the rail. **Figure 3-9** shows the proposed design of the whole rail.

3.3 Sector Gear for Rotation around Rail

The rotation mechanism around the rail is composed of the following devices:
- motor
- harmonic drive gearing
- multi-train epicycloidal reduction gear
- sector gear

Among these, the sector gear is one of key components for compact design. In the 1998 FDR, a spur gear was used for the sector gear. The diameter of the gear affects on the size, especially offset of the telescopic arm, and thus, a double helical gear is introduced to reduce the diameter. Generally, a helical gear has higher contact ratio than a spur gear, and thereby, it sustains higher torque.

Regarding the multi-train epicycloidal reduction gear, the following device is chosen:
- Provider: Nabtesco
- Type: RV-550
- Reduction ratio: 1/192.4
- Allowable torque (starting/stopping): 13.475 kN•m
- Allowable torque (peak): 26.95 kN•m
- Efficiency: 0.9

In this design, the allowable torque is decided as 17.97 kN•m considering a safety factor of 1.5.

Table 3-2 shows required torques for each module. The maximum torque is 123.5 kN•m and it defines specification for the sector gear for rotation around the rail. The torque should be reduced to 17.97 kN•m, and hence, the reduction ratio of the sector gear must be larger than 6.87. The minimum number of teeth is about 17 from the viewpoint of manufacture. Thus, the numbers of teeth are decided as 117 and 17 for the gear and pinion. The module of the gears is decided as eight according to JGMA 401-01 ("Bending Strength Formula of Spur Gears and Helical Gears", Japan Gear Manufacturers Association) and JGMA 402-01 ("Surface Durability Formula of Spur Gears and Helical Gears", ibid), so as to satisfy the maximum torque, 123.5 kN•m, and repetitions, 10,000.

Finally, the rotation mechanism is designed as shown in **Table 3-3**.

3.4 Other Actuation Mechanisms

Table 3-4 shows the actuation mechanism of the outer arm. The output force of the mechanism is 75.4 kN (7.69 ton) and is enough to handle the module.

Table 3-5 shows the rotation mechanism along the rail. The rated motor torque, 4.77 N•m, makes the higher output torque of the harmonic drive gearing than the allowable one. The required torque of this mechanism is decided by a toroidal scanning length to find the position of the No. 9 module. It needs 43.3 kN•m for the scanning length of 856 mm (16 degrees) and 49.3 kN•m for that of 1000 mm (18.5 degrees). Hence, the required torque is defined as 50 kN•m. In order to satisfy this, the motor must be operated with the torque of 4.48 N•m and the output torque of the harmonic drive gearing kept at 9.134 kN•m, lower than the aloowable one.

3.5 Vehicle Frame and Roller Arrangement

Using the guide rollers and the rotation mechanism selected in the previous subsections, the vehicle can be designed as shown in **Figs 3-10~3-12**. The diameter of the outer-bottom roller is changed to 120 mm while others are as is decided in **Subsection 3-2**. The reduction of rail cross-section and sector gear diameter shortens the offset of the telescopic arm from 1,130 mm in the 2001 FDR to 890 mm.

3.6 Conclusion of Compact Design

Table 3-6 summarizes the result of compact design comparing with the FDR designs. The compact design reduces the size of the manipulator drastically while the capacity increases. Preliminary kinematical analysis finds that the rail should be located at the center of the inscribed circle of the first wall. Thereby, the rail radius is changed to 6190 mm in **Table 3-6** while it was 6150 mm in the study in **Subsection 3.2**.

Table 3-1 Parameter Survey for Rail Design

Design Conditions:

Rail radius: 6,150 mm, Wall thickness of rail: 10 mm, Lib thickness of rail: 6 mm

Roller radius: 80 mm, No of rollers: 4 for each position (two bogies with two rollers)

Rail Width	Rail Height	Rail Weight per Length	Rail Weight (105·)	Joint Weight	Torsion Moment	Span of Inner/Outer Rollers	Load per Inner/Outer Roller	Weight of Vehicle/ Manipulator and Module	Load per Top Roller	Roller Position	Roller Length	Hertz's Stress
mm	mm	kg/mm	kN	kN	kN·m	mm	kN	kN	kN		mm	MPa
250	600	0.152	16.671	5.096	31.32	361	43.385	150.332	37.583	top/bottom	175	439.7356374
										inner	220	419.8511748
										outer	250	396.5481024
250	550	0.144	15.809	4.671	28.91	348.5	41.475	150.332	37.583	top/bottom	175	439.7356374
										inner	195	436.0253015
										outer	200	433.4840937
250	500	0.136	14.948	4.247	26.49	336	39.423	150.332	37.583	top/bottom	175	439.7356374
										inner	170	455.2859359
										outer	150	488.0027095
250	450	0.129	14.087	3.822	24.08	323.5	37.212	150.332	37.583	top/bottom	175	439.7356374
										inner	145	478.9514583
										outer	100	580.6770586
250	400	0.121	13.226	3.397	21.66	311	34.823	150.332	37.583	top/bottom	175	439.7356374
										inner	120	509.3054128
										outer	50	794.4070321

σ_a=874 MPa (SM570)

Table 3-2 Required Torque for each Module

Module No.	Torque (kN•m)	Number of Modules
1	79.7	18
2	73.6	18
3	86.8	18
4	87.6	18
5	76.2	18
6	67.6	18
7	62.1	18
8	48	18
9	64.8	18
10	16	18
11	19.1	36
12	48.5	36
13	94.5	36
14	100.9	32
15	93.3	32
16	70.7	35
17	53.5	36
18	8.1	36
14C	112.2	1
14S	123	3
15C	123.5	1
15S	71.4	3
16C	71.6	1

Table 3-3 Rotation Mechanism around Rail

Devices	Motor	Harmonic Drive Gearing	Multi-Train Epicycloidal Reduction Gear	Sector Gear
Provider	Tamagawa Seiki	Harmonic Drive Systems	Nabtesco	–
Type	TS4817N9007E435	HPG-32A-21	RV-550	–
Reduction Ratio	–	1/21	1/192.4	17/117
Efficiency	–	0.9	0.9	0.95
Allowable Torque	–	300 N•m	13.475 kN•m	–
Power	2 kW	–	–	–
Rated Torque	6.8 N•m	128.52 N•m	22.255 kN•m	145.505 kN•m
Rated Speed	3000 rpm	143 rpm	0.743 rpm	0.108 rpm (38.8 deg/min)
Required Torque for Module 15C	5.8 N•m	110 N•m	18.889 kN•m	123.5 kN•m

Table 3-4 Actuation Mechanism of Outer Arm

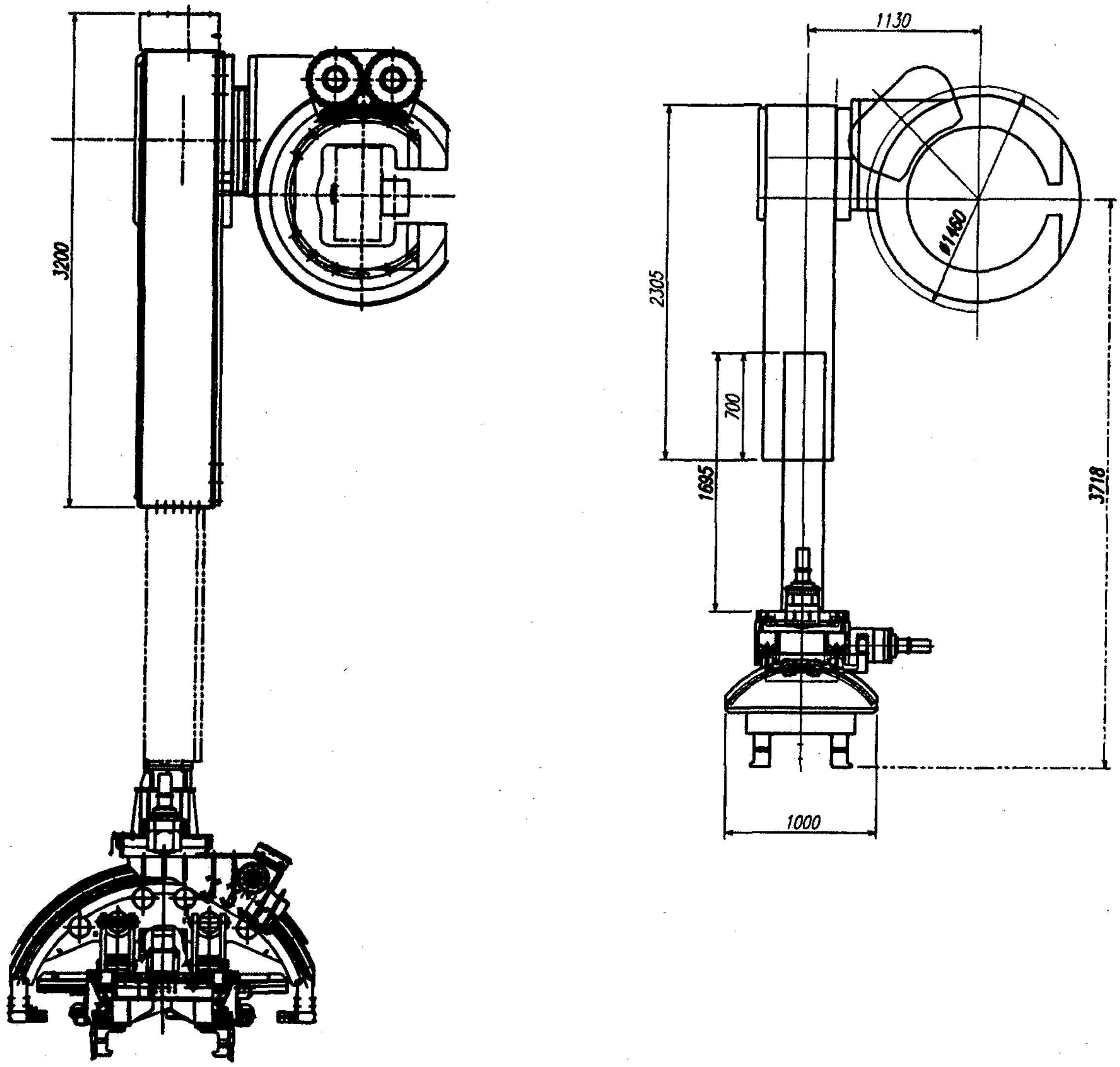
Devices	Motor	Ball Reducer	Harmonic Drive Gearing	Rack and Pinion
Provider	–	Kamo Seiko	Harmonic Drive Systems	–
Type	–	BR-160UH-20-19K	CSF-100-120-2A	–
Reduction Ratio	–	1/20	1/120	(PCD=184mm)
Efficiency	–	0.85	0.75	0.95
Allowable Torque	–	98 N•m	7.299 kN•m	–
Power	1.5 kW	–	–	–
Rated Torque	4.77 N•m	81.1 N•m	7.299 kN•m	75.361 N
Rated Speed	3000 rpm	150 rpm	1.25 rpm	722.6 mm/min (12.0 mm/sec)

Table 3-5 Rotation Mechanism along Rail

Devices	Motor	Ball Reducer	Harmonic Drive Gearing	Spur Gear
Provider	–	Kamo Seiko	Harmonic Drive Systems	–
Type	–	BR-160UH-20-19K	CSF-100-160-2A	–
Reduction Ratio	–	1/20	1/160	21/121
Efficiency	–	0.85	0.75	0.95
Allowable Torque	–	98 N•m	9.180 kN•m	–
Power	1.5 kW	–	–	–
Rated Torque	4.77 N•m	81.1 N•m	9.731 kN•m	53.26 kN•m
Rated Speed	3000 rpm	150 rpm	0.938 rpm	0.163 rpm (58.6 deg/min)
Required Torque for Module 9	4.48 N•m	76.1 N•m	9.134 kN•m	50 kN•m

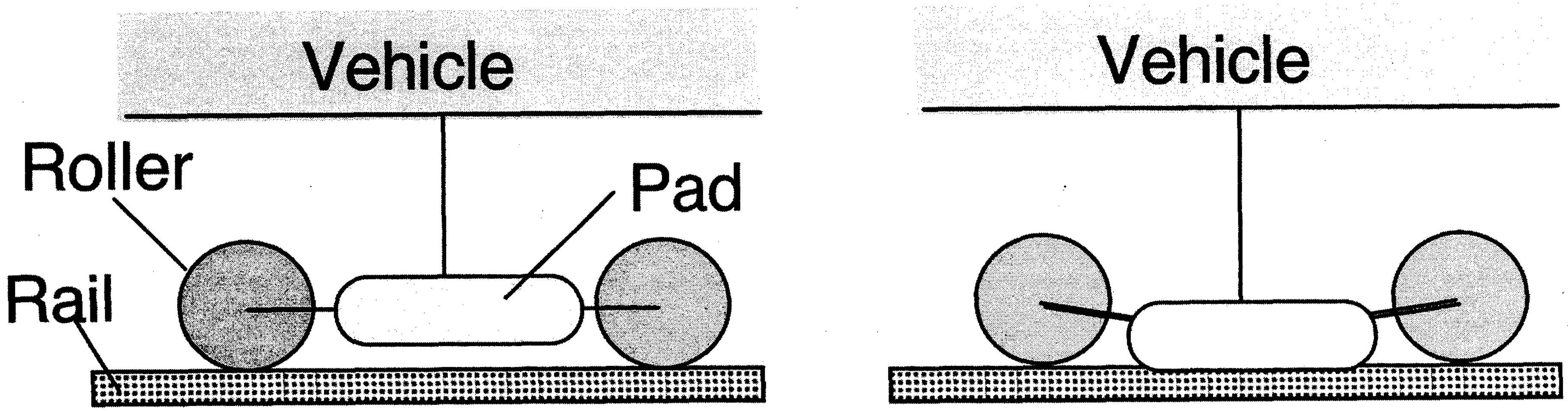
Table 3-6 Comparison of Proposed Design with FDRs

	FDR 1998	FDR 2001	Proposed Design
Whole System			
Center of Rail (R, Z)	–	6100 mm, 1020 mm	6190 mm, 1020 mm
Rail Size (H, W)	600 mm, 300 mm	500 mm, 250 mm	400 mm, 250 mm
Offset	1220 mm	1130 mm	950 mm
Total Weight	13.373 ton (measured value of prototype in EDA)	11.2 ton (DDD Ch. 3, p. 25)	8 ton (to be confirmed)
Rotation around Rail			
Required Torque	98 kN•m	–	123.5 kN•m
Sector Gear	Spur Gear	–	Double Helical Gear
Pitch Circle Diameter	1410 mm	1460 mm	996.1 mm
Inner Arm			
Length	2695 mm	1695 mm	1830 mm
Stroke	1725 mm	975 mm	1185 mm
Linear Guide	4/rail	–	2/rail
Length in Outer Arm at Max. Stroke	995 mm	700 mm	625 mm
Pitch of Linear Guide	485 mm	–	400 mm
Outer Arm			
Length	3200 mm	2475 mm	2155 mm
Stroke	1800 mm	1532 mm	1473 mm
Linear Guide	4/rail	–	2/rail (3 rails)
Space for Linear Guide	1100 mm	718 mm	650 mm
Pitch of Linear Guide	765 mm	–	410 mm
Rotation along Rail			
Offset of Axis	350 mm	200 mm	0 mm
Required Torque	–	–	50 kN•m
End Effector			
Weight	1.44 ton	–	1.0 ton



FDR 1998 **FDR 2001**

Fig. 3-1 Comparison of FDR Designs in 1998 and 2001



(a) During Rail Deployment / Vehicle Movement

(b) During Module Grappling

Fig. 3-2 Concept of Roller Mechanism with Pad

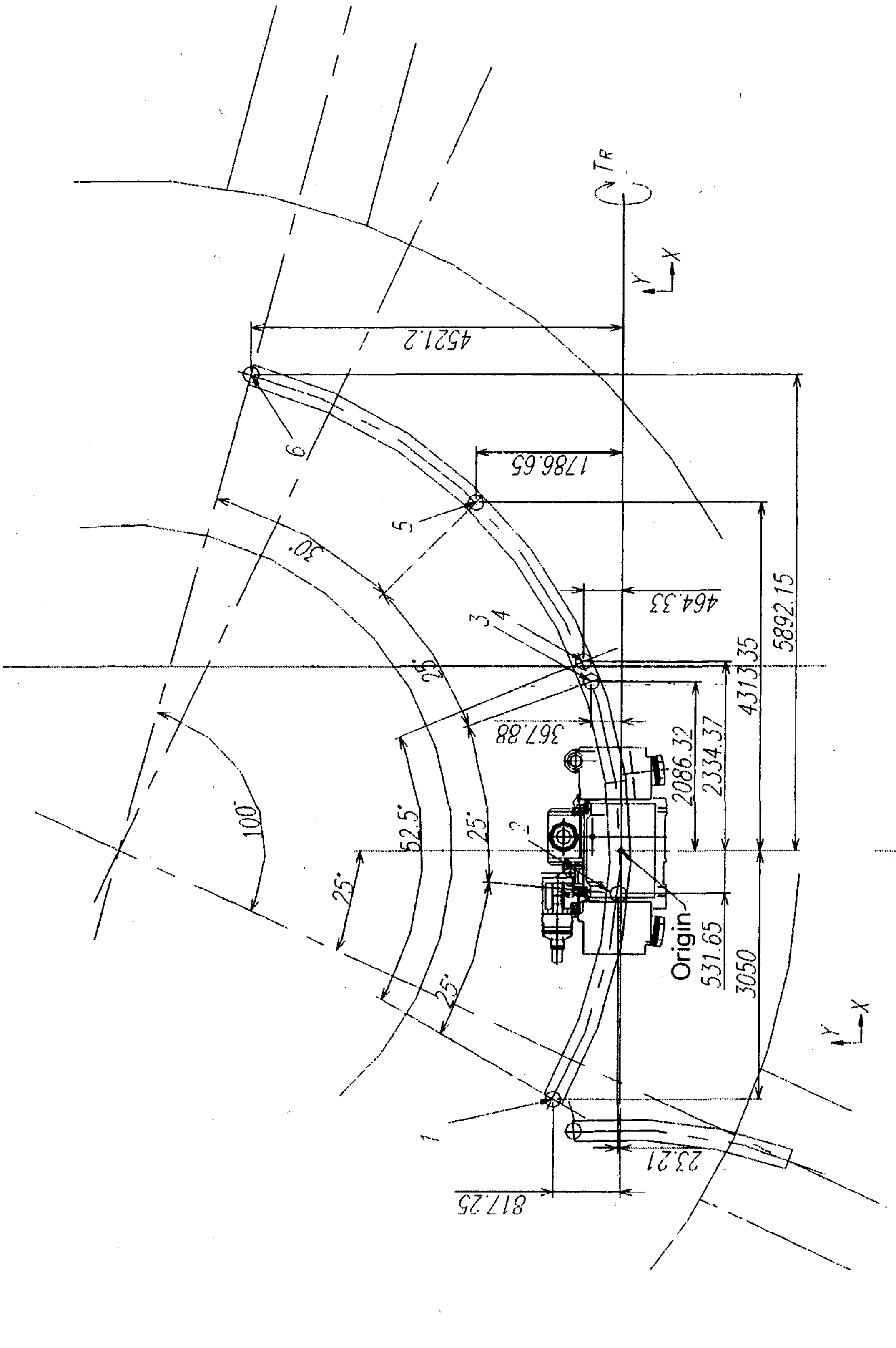


Fig. 3-3 Load Condition with Rail Deployed 105 Degrees

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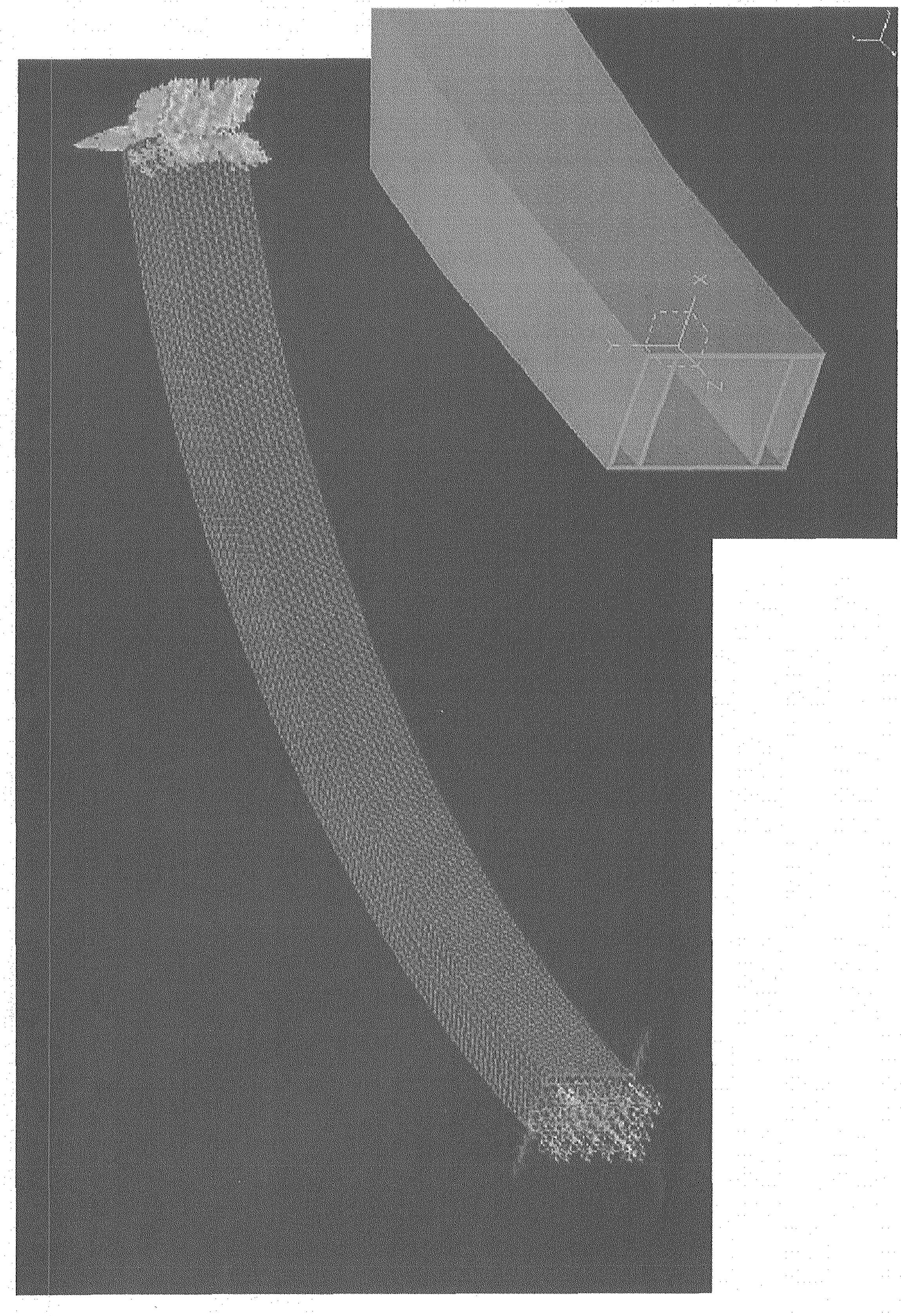

Fig. 3-4 Analysis Model of Rail

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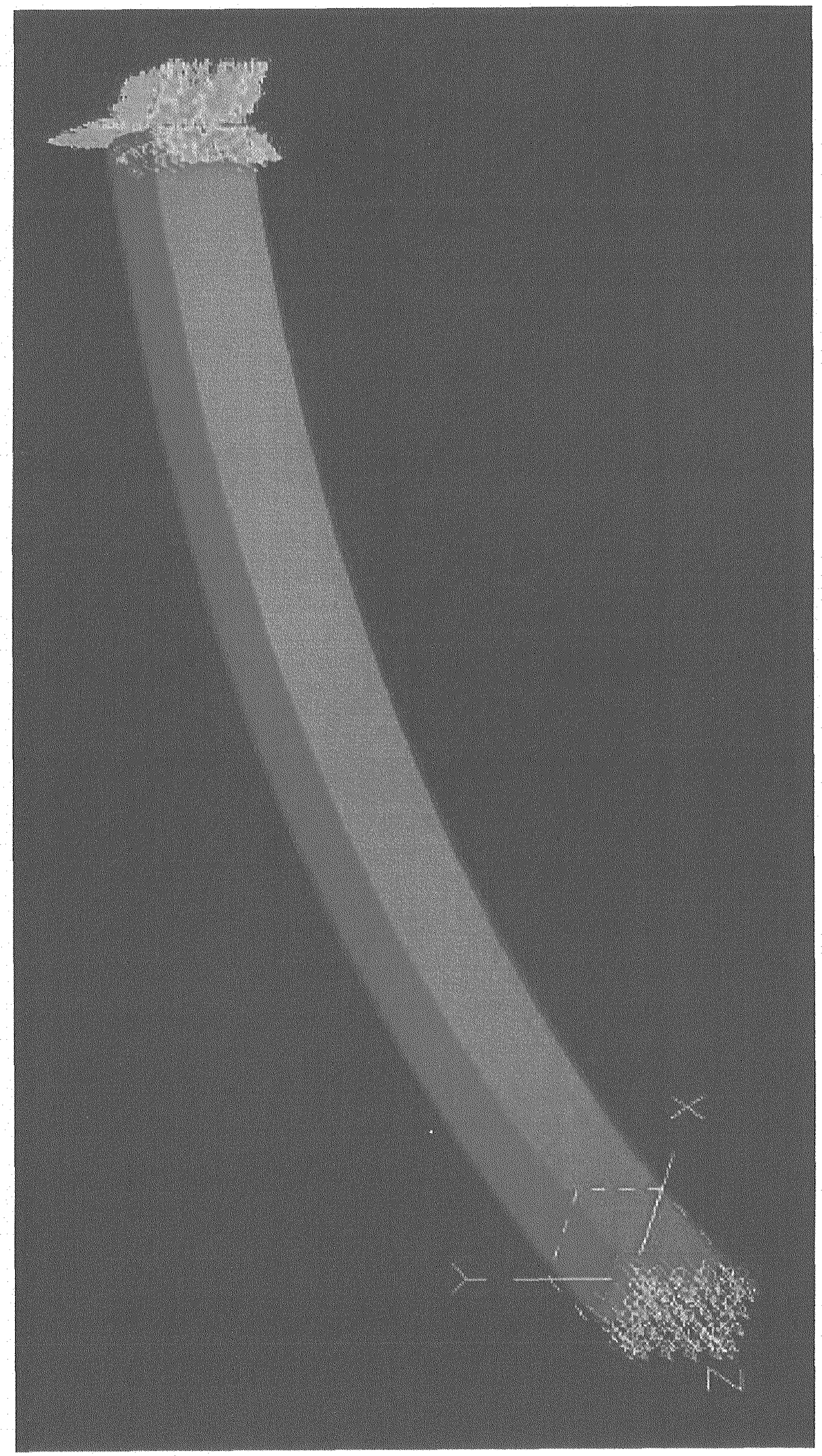

Fig. 3-5 Boundary Condition

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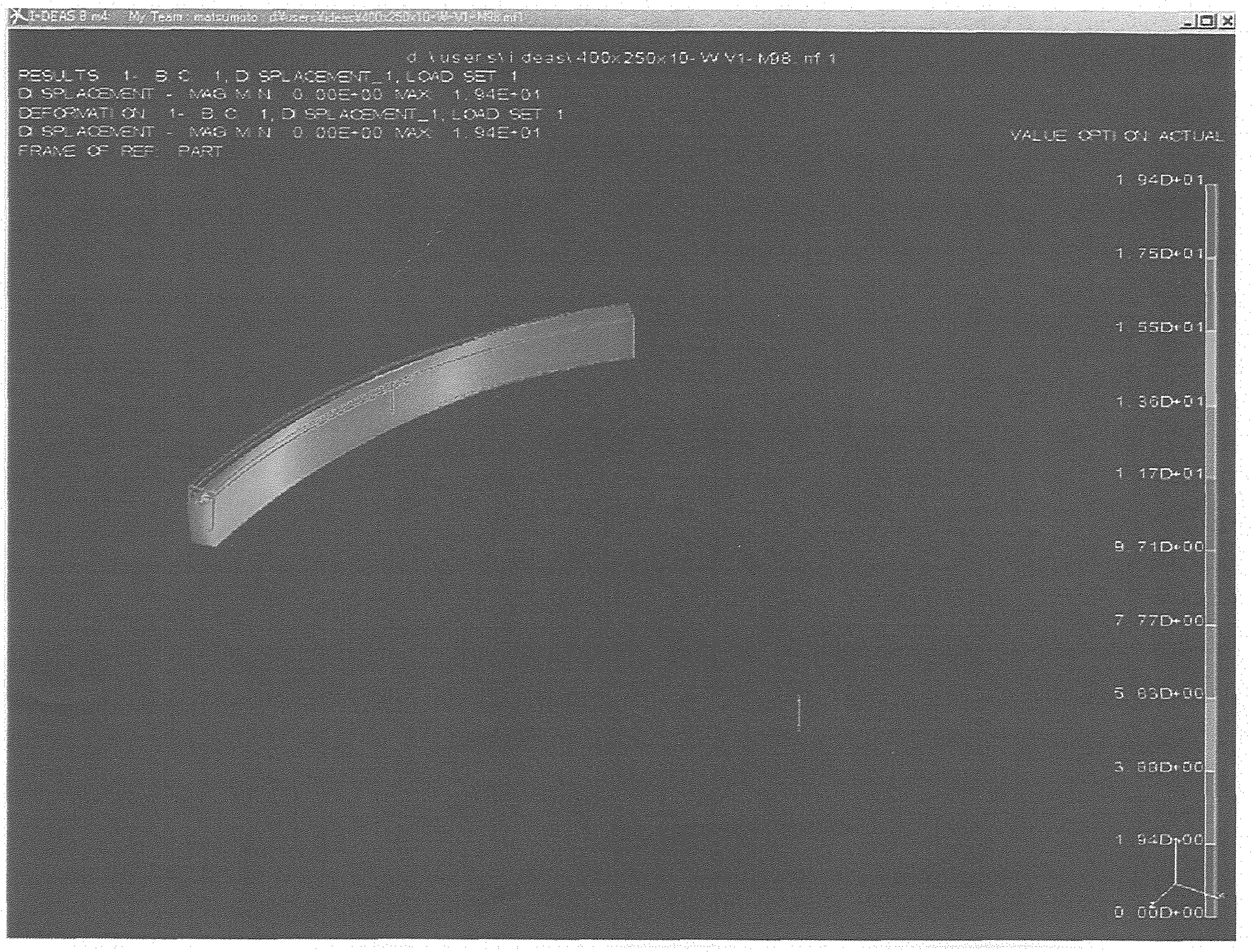

Fig. 3-6 Displacement of Rail

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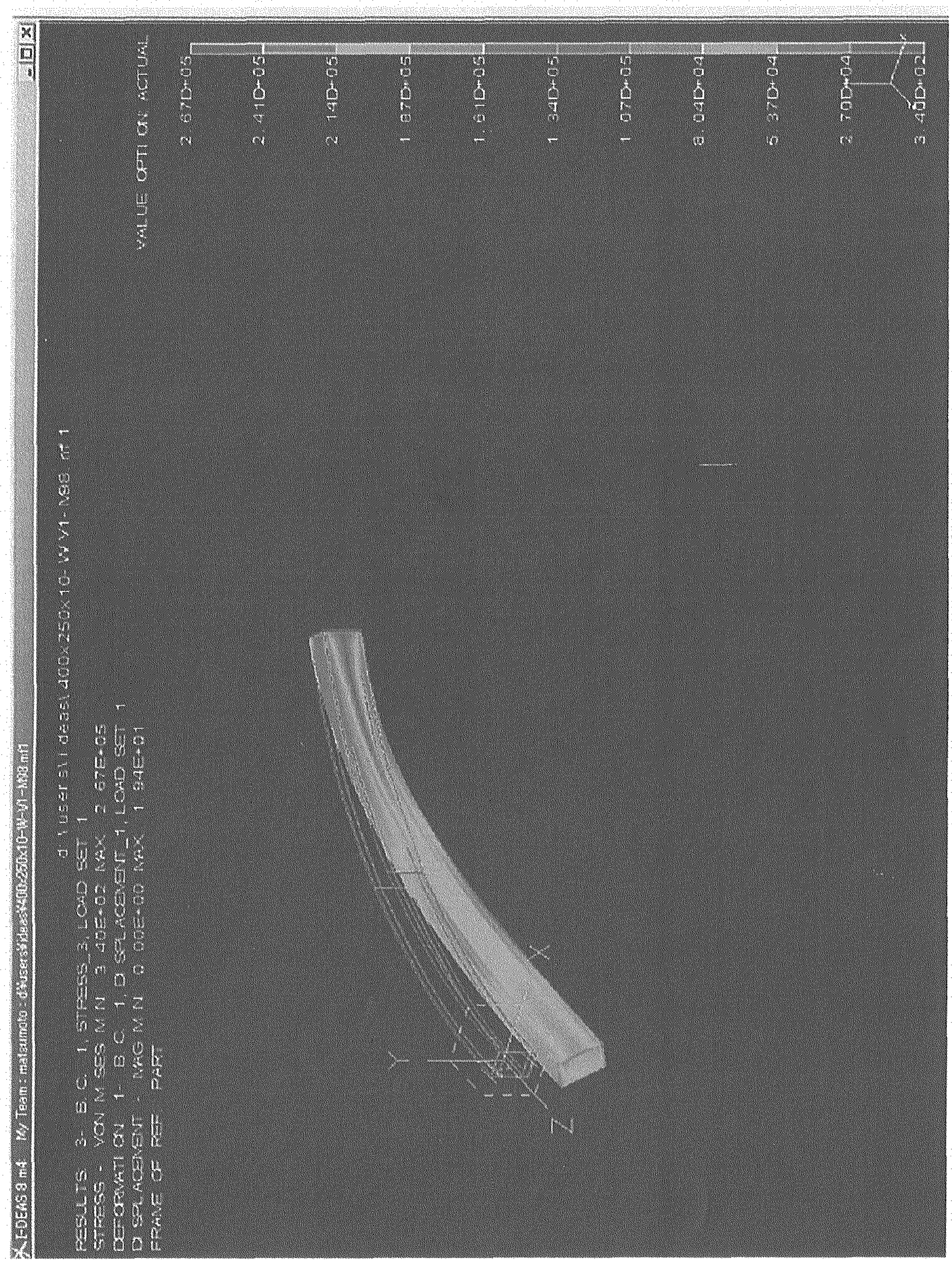

Fig. 3-7 Mises Stress of Rail

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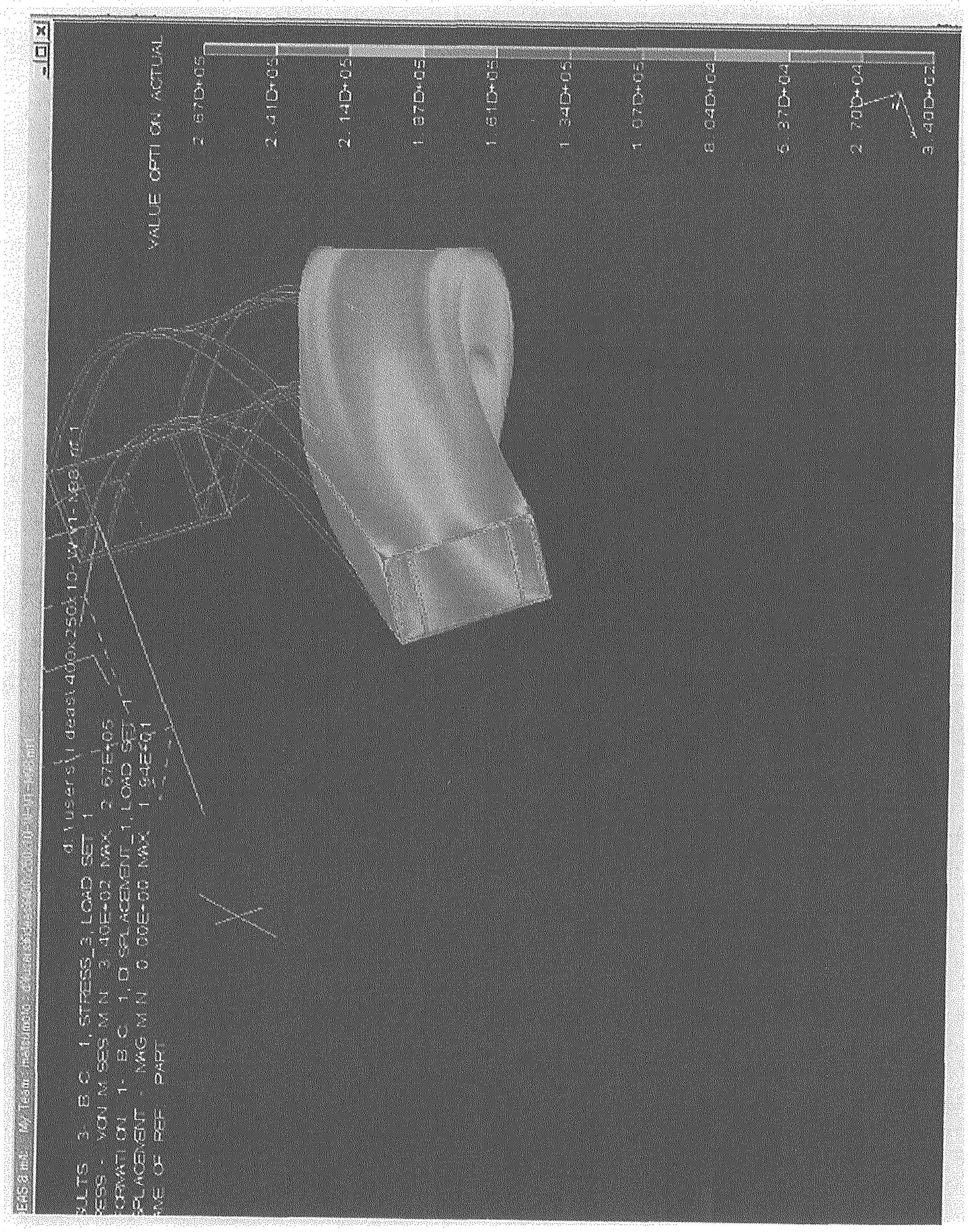

Fig. 3-8 Mises Stress of Rail (Fixed End)

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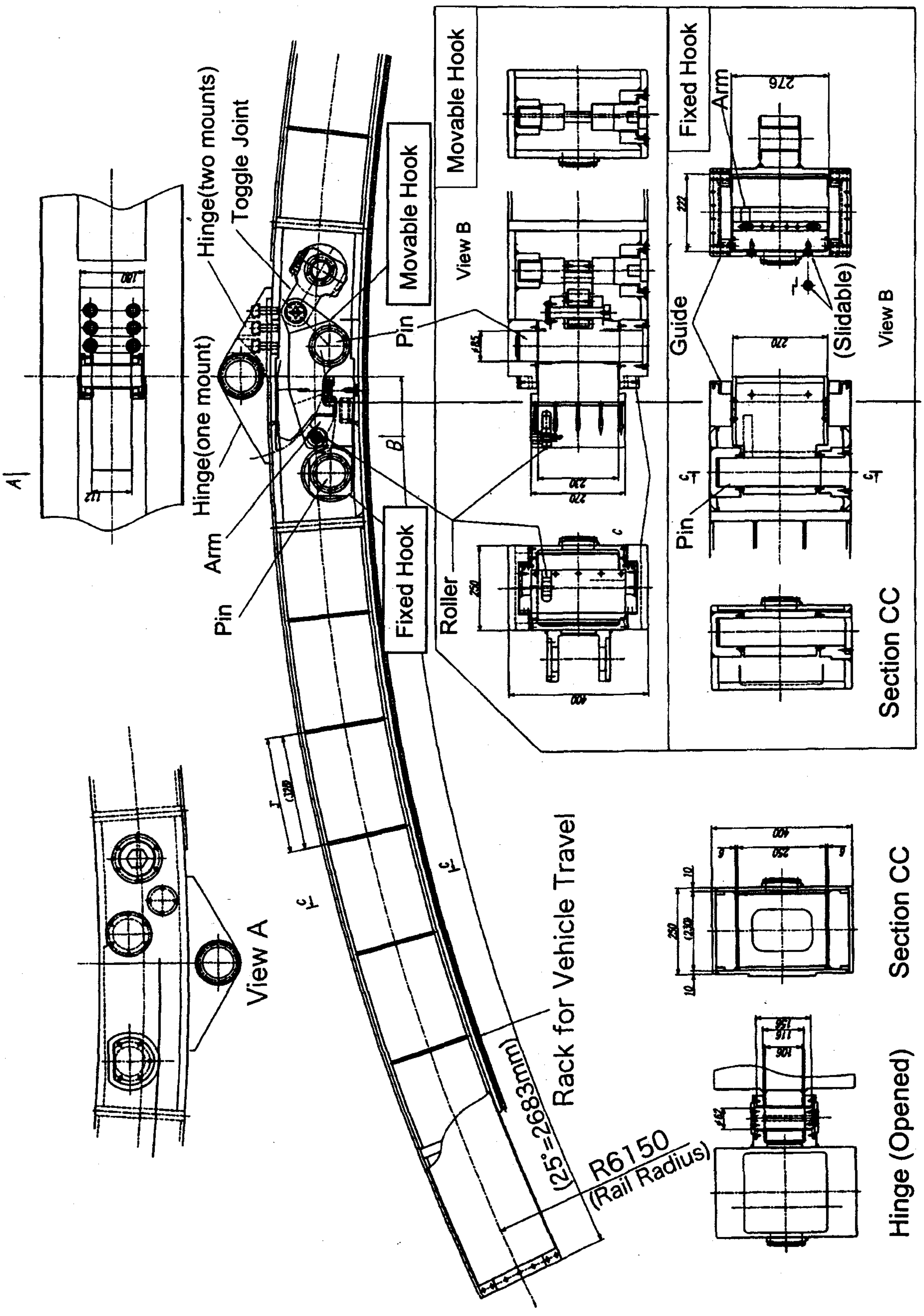

Fig. 3-9 Proposed Design of Articulated Rail

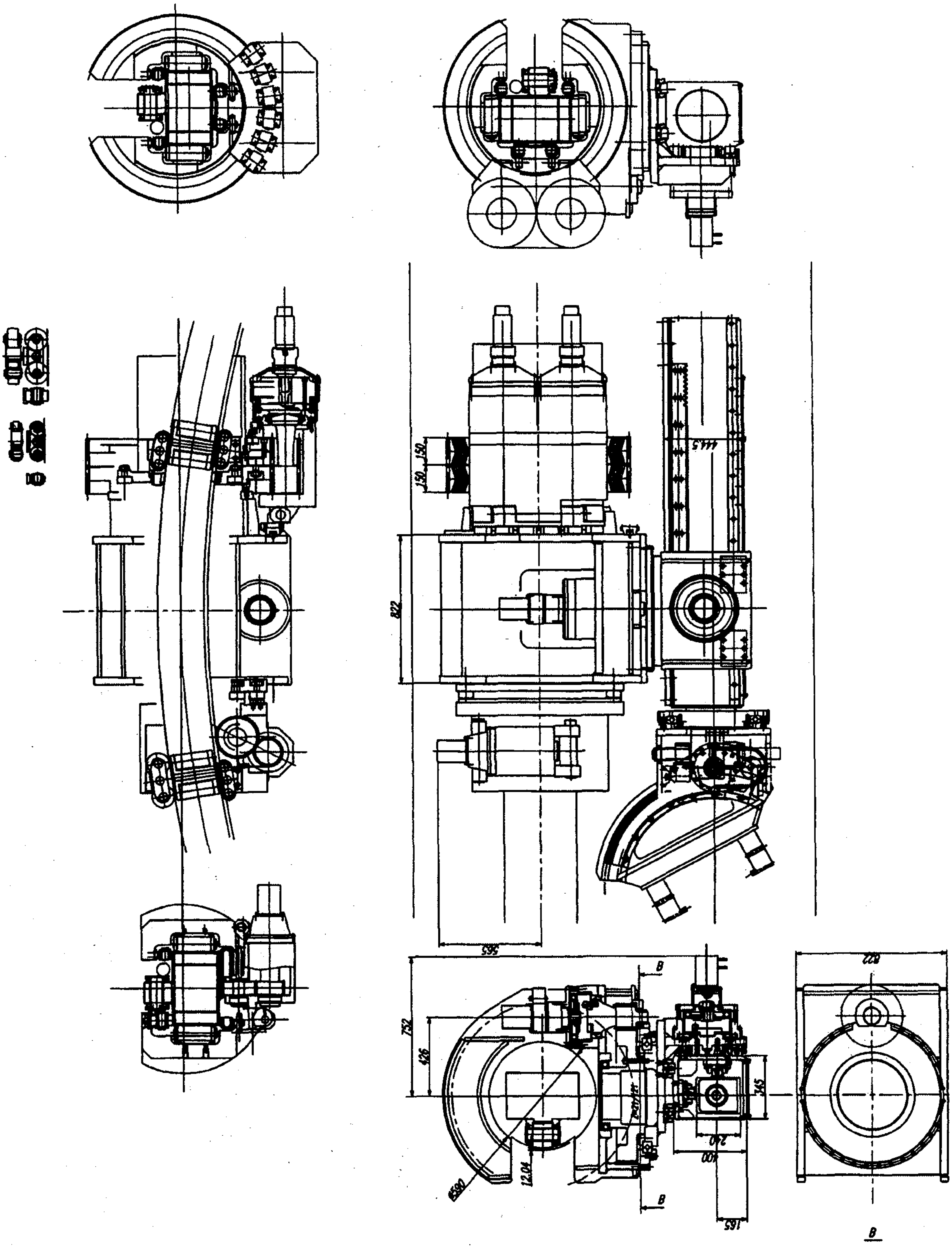

Fig. 3-10 Proposed Design of Vehicle/Rail Manipulator (1)

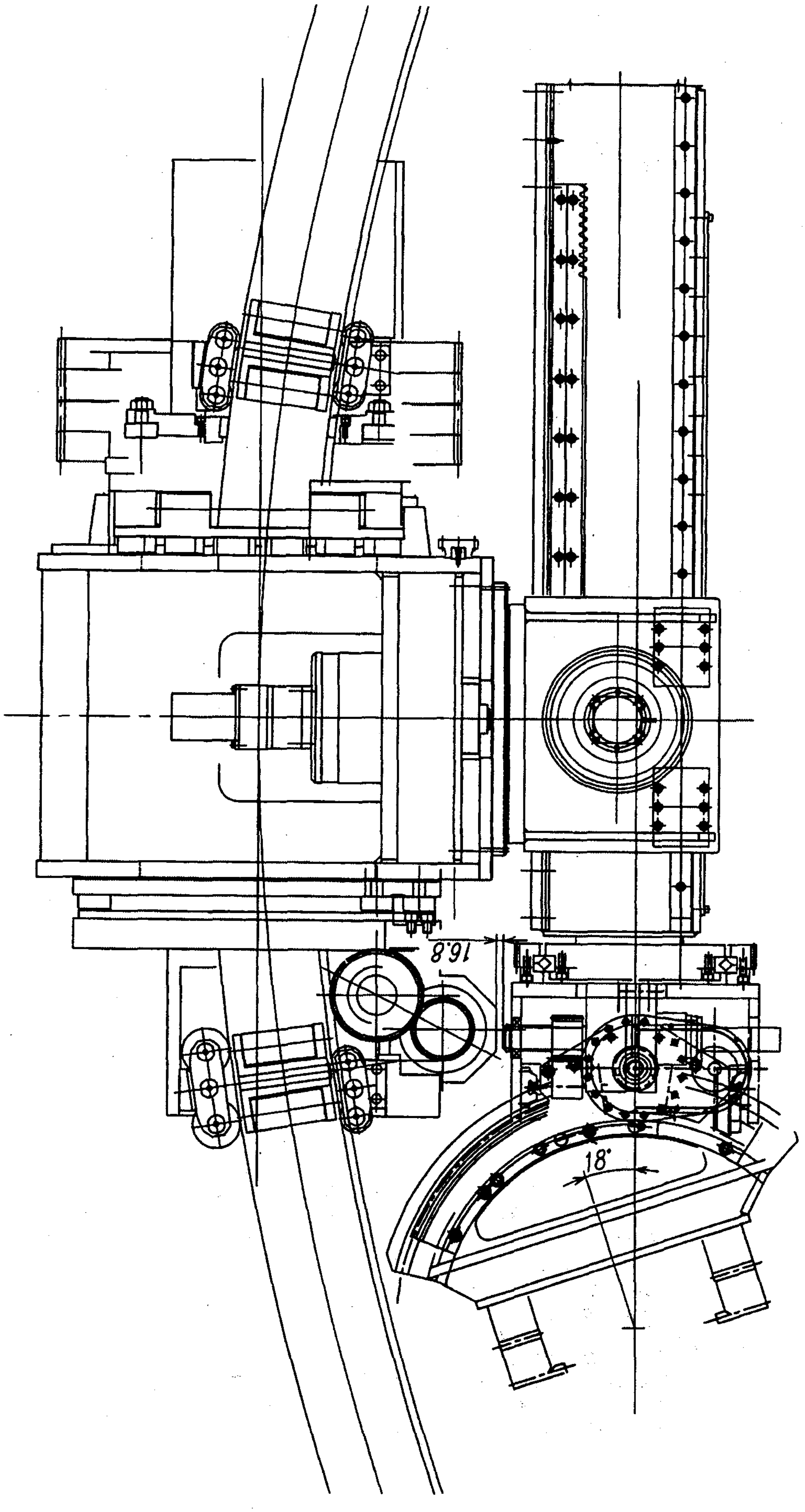

Fig. 3-11 Proposed Design of Vehicle/Rail Manipulator (2)

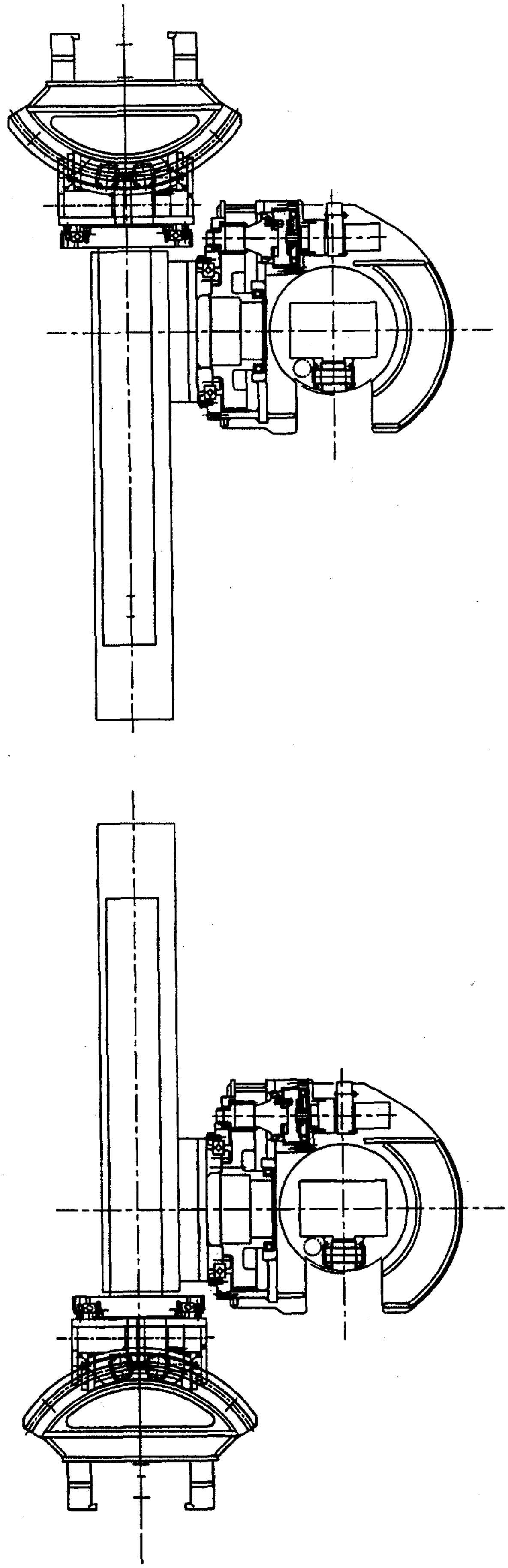

Fig. 3-12 Proposed Design of Vehicle/Rail Manipulator (3)

4. KINEMATICAL CAD ANALYSIS FOR BLANKET REPLACEMENT

In order to check feasibility of the proposed design, a kinematical CAD analysis is performed for blanket replacement. As mentioned in **Subsection 2.2**, there was difficulty to replace the modules No. 4, 9 and 12 in the old design. This kinematical analysis aims at transportation of the modules around them.

4.1 Modules No. 4 to 8

Figures 4-1~4-3 shows results of the kinematical analysis for replacement of the modules No. 4 to 8. As shown in **Fig. 4-1**, the working area for replacement is defined so that the module and manipulator keep distance of 100 mm from the first wall. The target circle is also defined so as to be cocentric with the inscribed circle of the first wall and to have a radius 100 mm smaller than it. During rotation around the rail, the module and manipulator must not cross the target circle. With the module adjusted to the target circle, there is a gap of 16.81 mm between the end of the outer arm and the target circle as shown in **Fig. 4-1**. Thus, the manipulator can be rotated around the rail with adequate distance from the first wall as shown in **Figs. 4-2 and 4-3**.

4.2 Modules No. 9 to 12

Figures 4-4~4-9 shows results of the kinematical analysis for replacement of the modules No. 9 to 12. With the module adjusted to the target circle, the end of the outer arm exceed the target circle by 29.25 mm as shown in **Fig. 4-4**. Hence, the outer arm must advance about 20 mm as shown in **Fig. 4-5**. The module exceeds from the target circle by 12.61 mm but it stays still inside of the working area. The manipulator can be thereby rotated counterclockwise until the module crosses the working area as shown in **Fig. 4-6**. After that, the outer arm must retreat about 20 mm as shown in **Fig. 4-7** so that the module does not exceed the working area during further counterclockwise rotation as shown in **Fig. 4-8**. Finally, the manipulator is rotated along the rail to pass the module as shown in **Fig. 4-9**.

4.3 Stroke of Manipulator

The No. 8 module needs the longest stroke among modules and there is 99.9 mm more stroke even for that module as shown in **Fig. 4-10**. The manipulator, hence, can reach all of the modules in the proposed design.

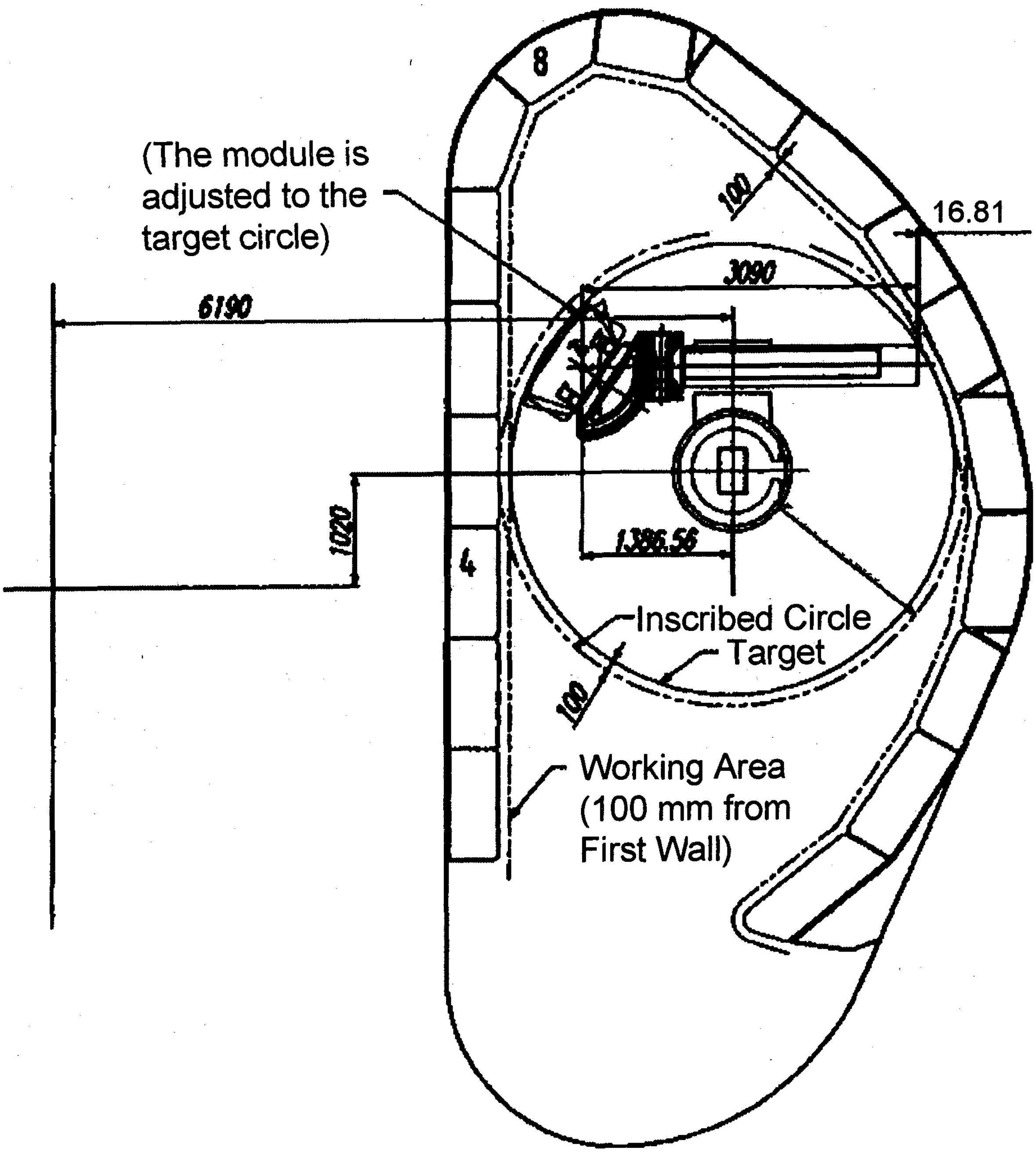

Fig. 4-1 Rotation around the Rail after the No. 4~8 Module (1)

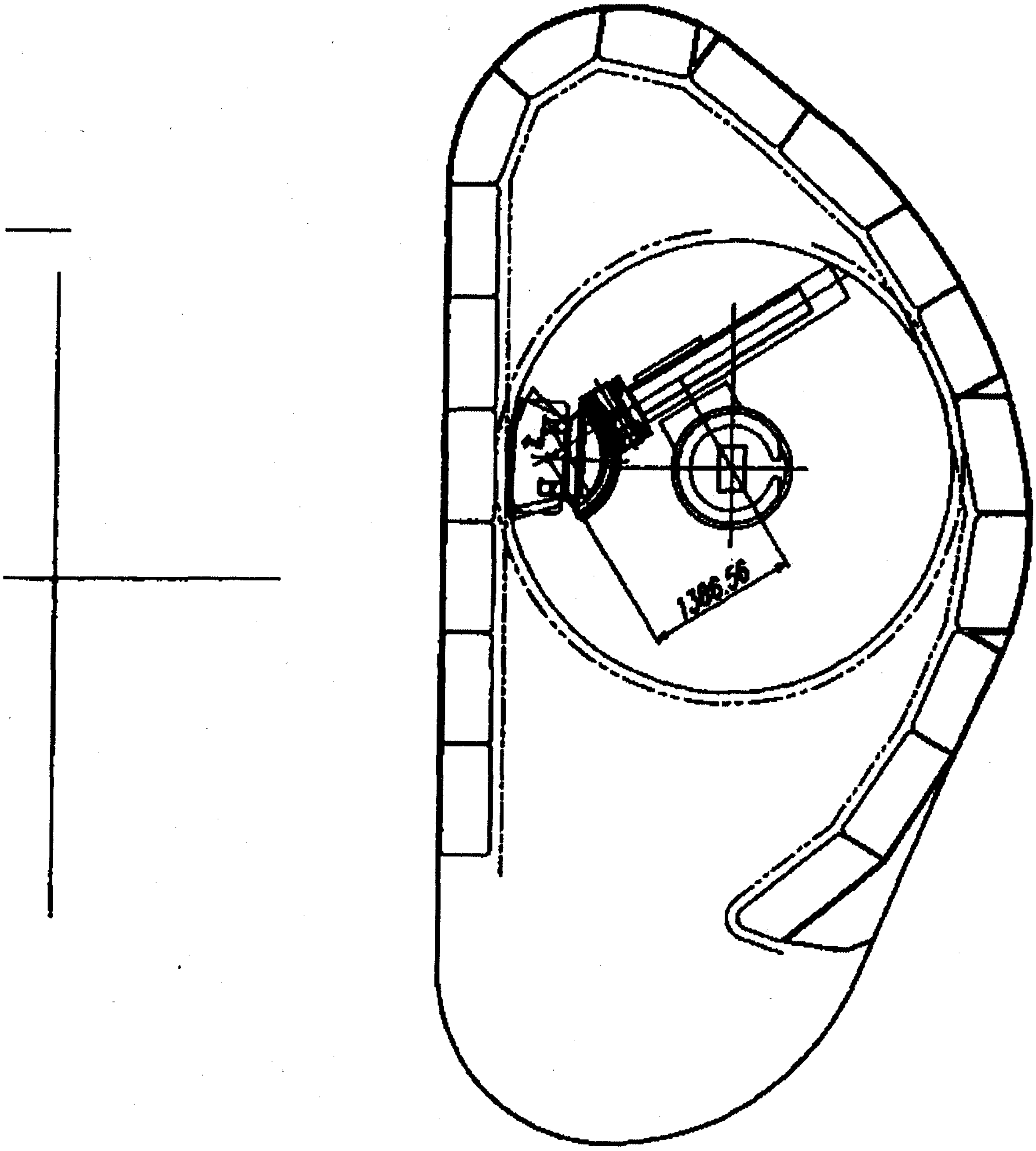

Fig. 4-2 Rotation around the Rail after the No. 4~8 Module (2)

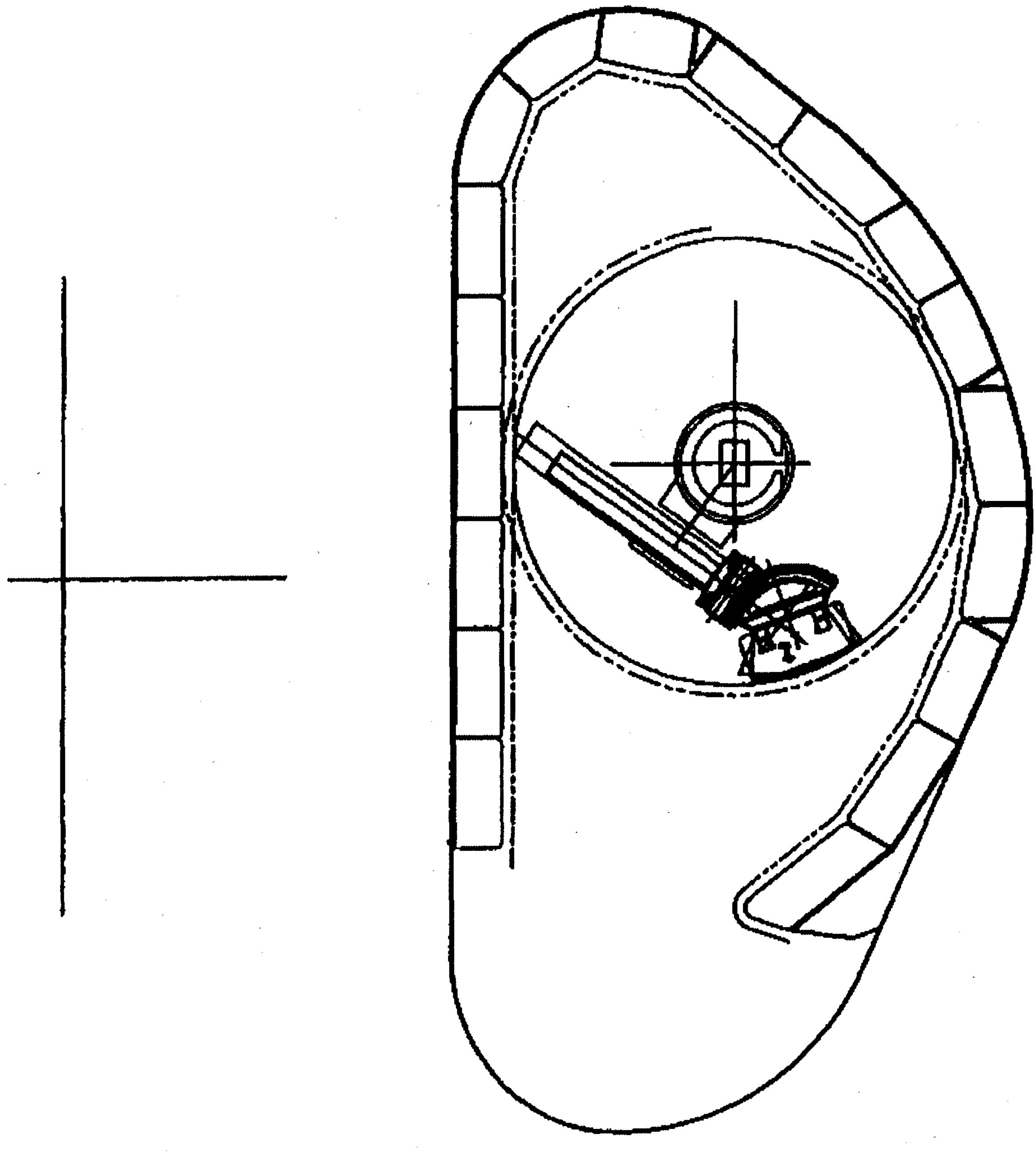

Fig. 4-3 Rotation around the Rail after the No. 4~8 Module (3)

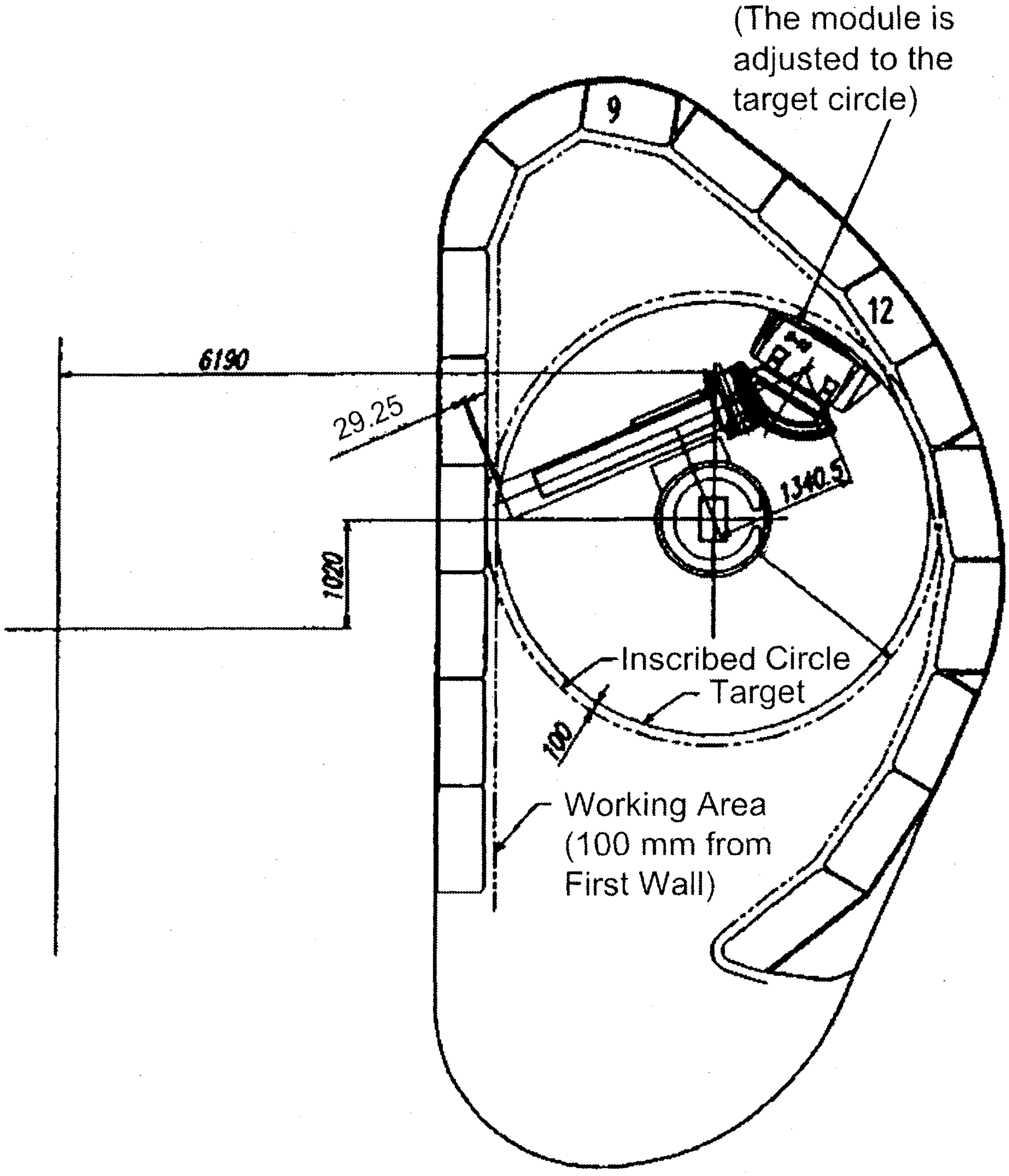

Fig. 4-4 Rotation around the Rail after the No. 9~12 Module (1)

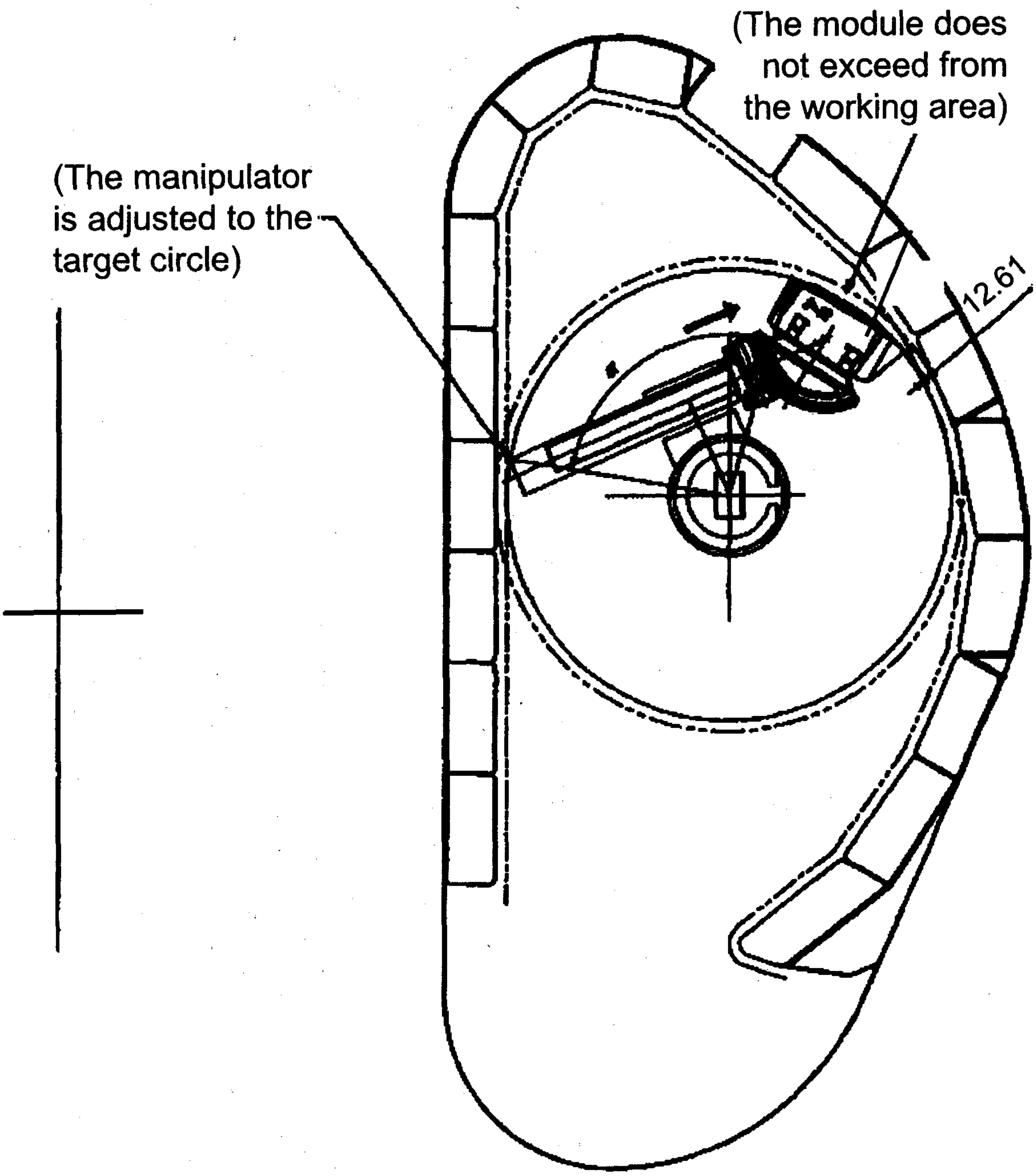

Fig. 4-5 Rotation around the Rail after the No. 9~12 Module (2)

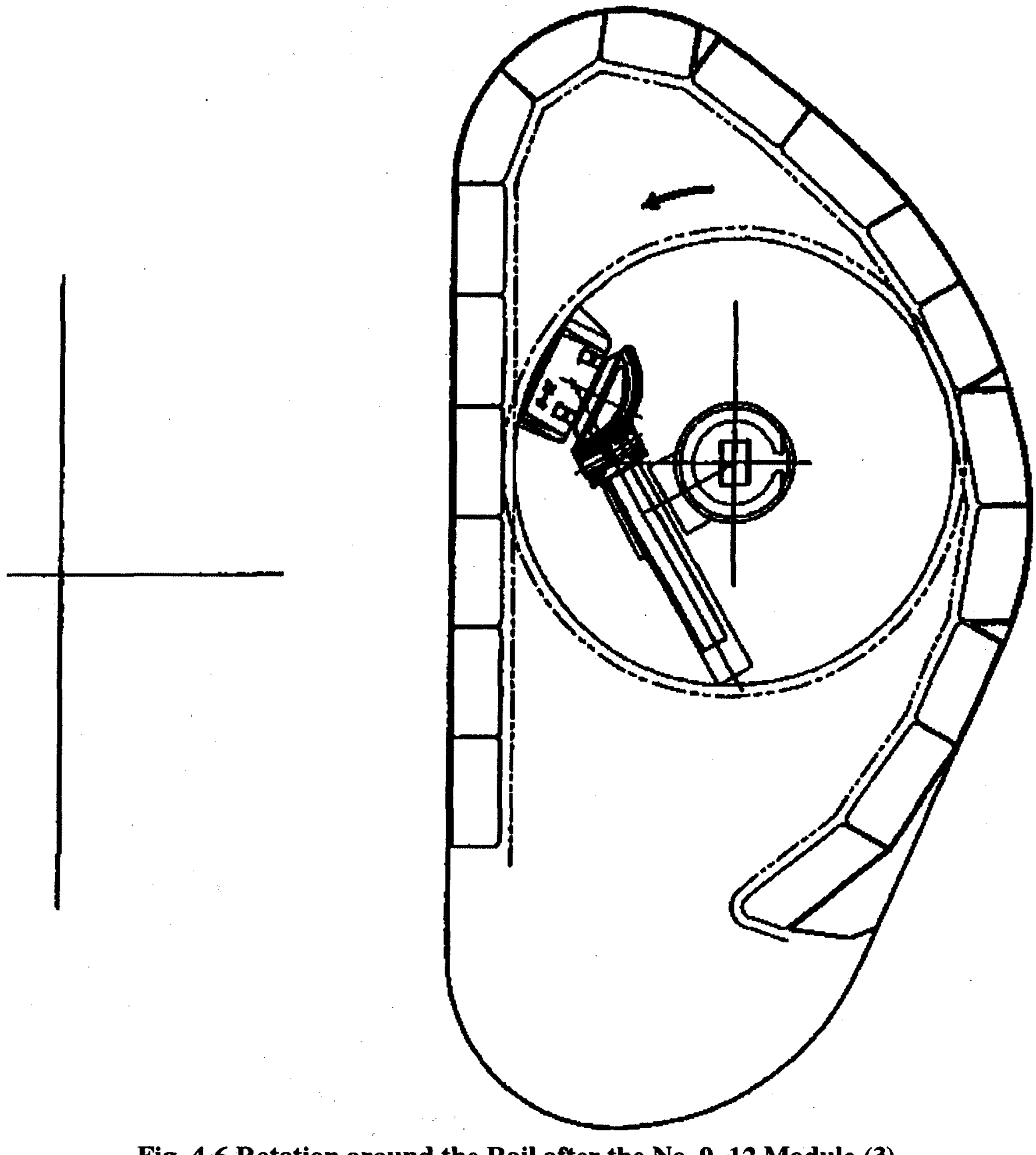

Fig. 4-6 Rotation around the Rail after the No. 9~12 Module (3)

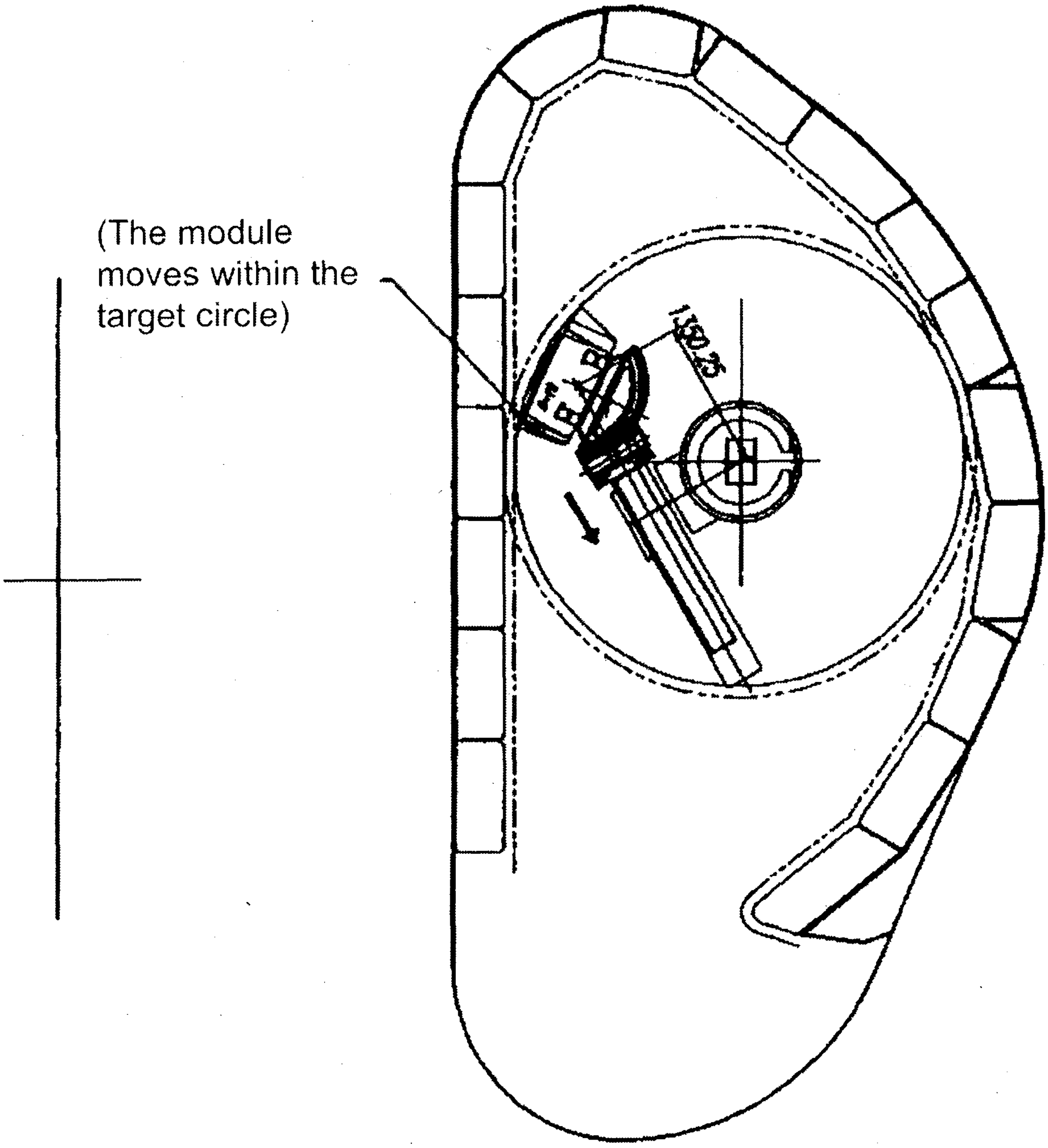

Fig. 4-7 Rotation around the Rail after the No. 9~12 Module (4)

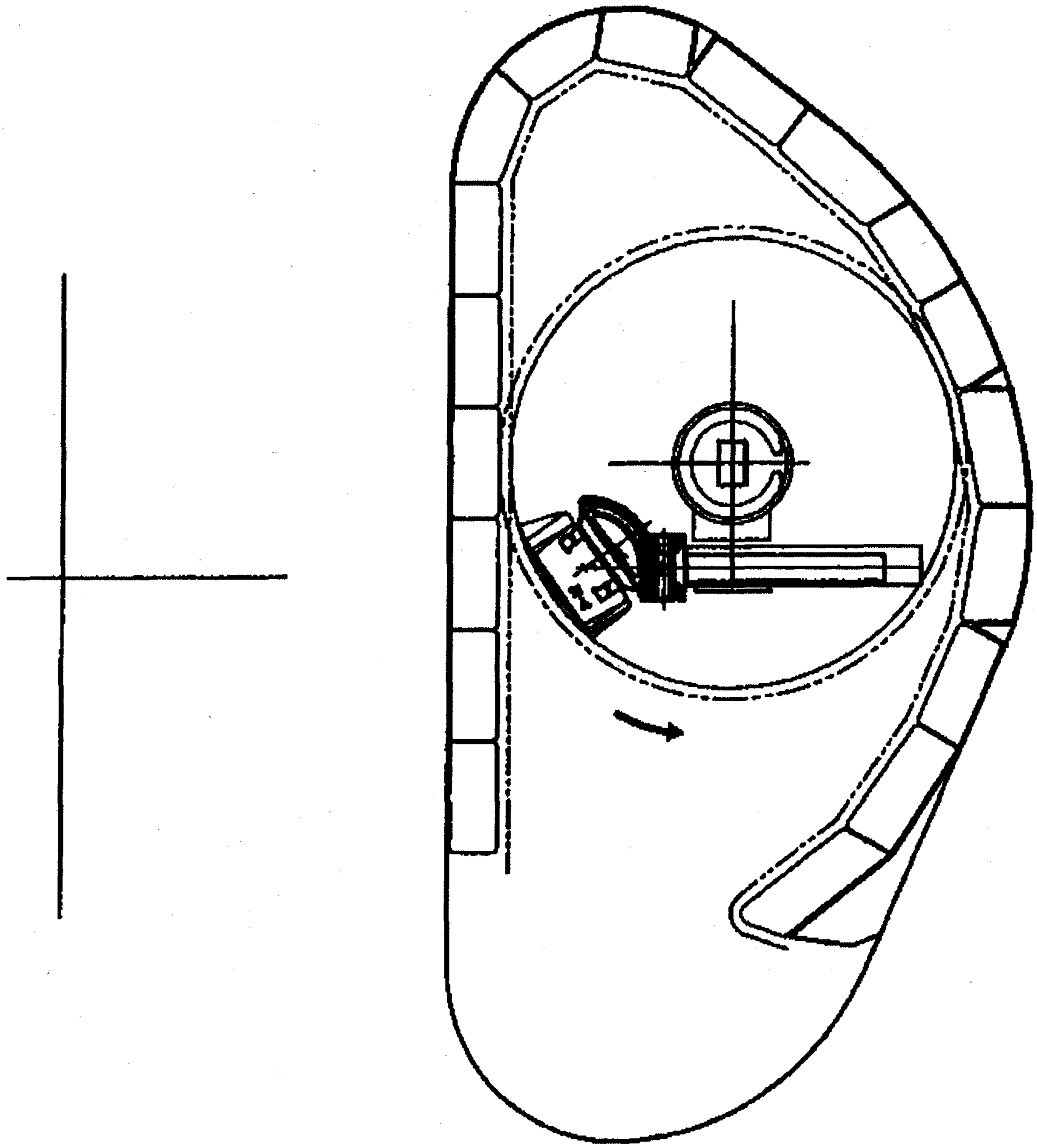

Fig. 4-8 Rotation around the Rail after the No. 9~12 Module (5)

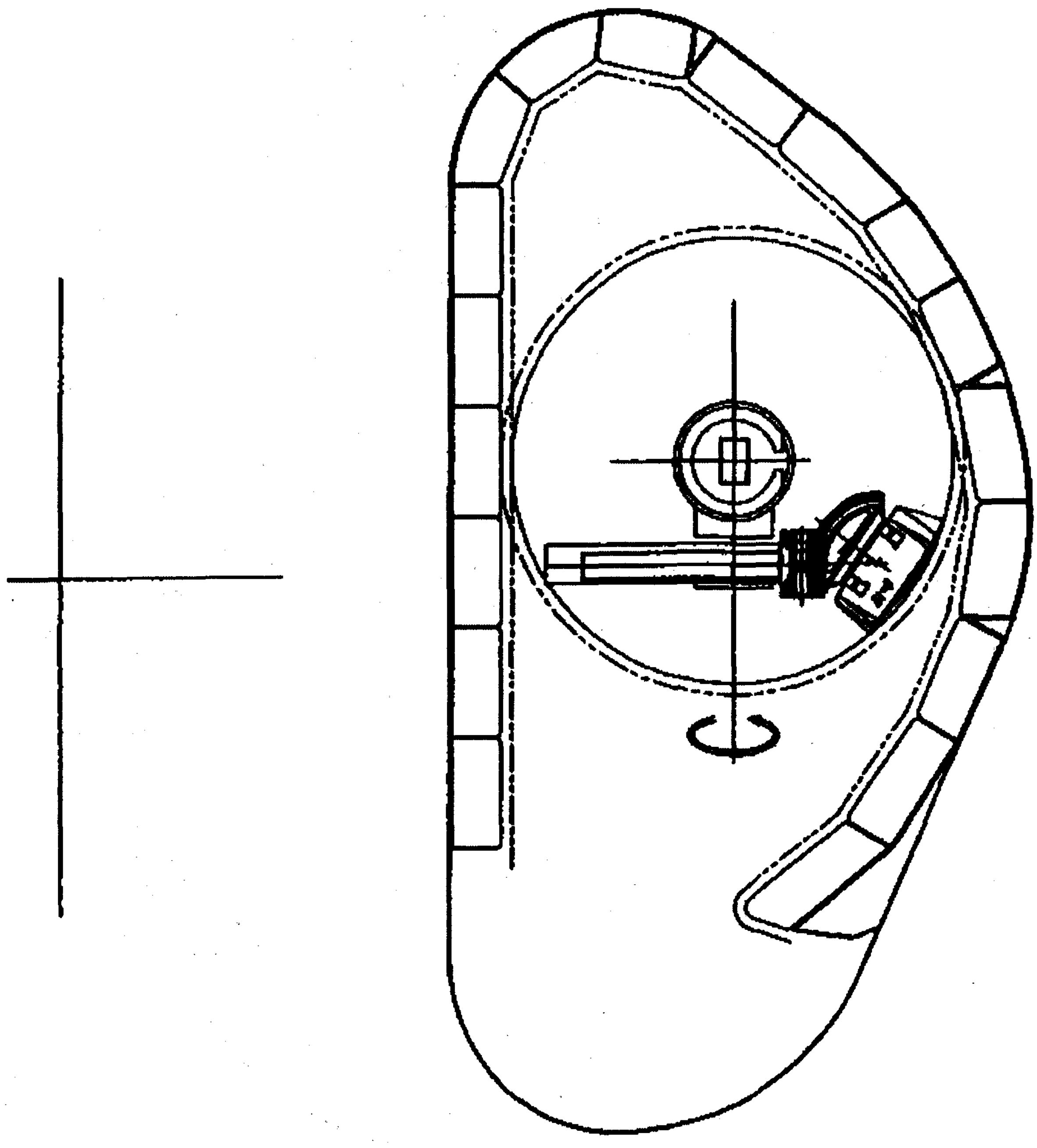

Fig. 4-9 Rotation around the Rail after the No. 9~12 Module (6)

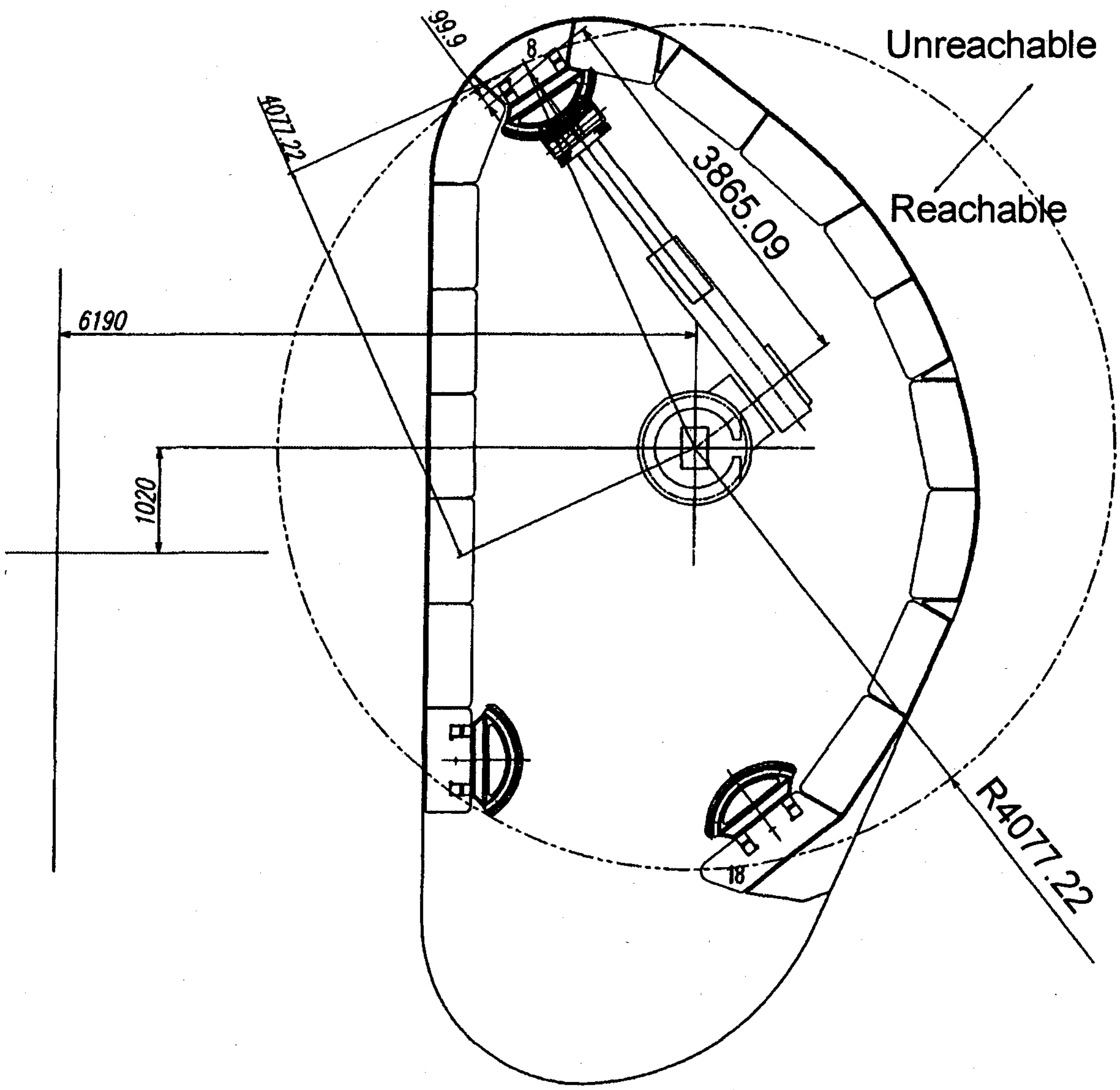

Fig. 4-10 Stroke during No. 8 Module

5. UPDATE OF LOAD CONDITION AND DESIGN CONDITIONS BASED ON COMPACT DESIGN

5.1 Guide Roller

According to the compact design, the loads and moments induced by the rail are recalculated as shown in **Table 5-1**. Location and weight of each component is shown in **Fig. 5-1**. Considering them, the load and design condition of the guide roller is updated as shown in **Table 5-2**. It is confirmed that the Hertz Stress is under the allowable one after the compact design.

5.2 Actuation Mechanisms

The updated load conditions of the actuation mechanisms are summarized in **Table 5-3**. All the mechanisms can realize the required load.

Table 5-1 Moments Induced during Rail Deployment

- Radius of Rail: 6190 mm
- Weight of Rail per Length: 1.183 N/mm
- Angle of Rail: 90 degree
- Length of Rail: 9723 mm
- Total Weight of Rail: 11.503 kN
- Weight of Joints (temporary value): 1.6985 kN

No.	Weight (kN)	Component	Position		Moment	
			X (mm)	Y (mm)	Bending Mr (kN•m)	Torsion Tr (kN•m)
1	1.6985	One Joint	-2368.81	471.19	-4.023	0.800
2	3.3970	Two Joints	807.96	52.96	2.745	0.180
3	11.5030	CoG of Rail	2368.81	471.19	27.247	5.420
4	3.3970	Two Joints	3768.23	1279.14	12.801	4.345
5	1.6985	One Joint	5718.81	3821.19	9.713	6.490
Sum	21.6940				48.483	17.236

Table 5-2 Load and Design Condition of Guide Roller

Span of Inner/Outer Rollers	Load per Inner/Outer Roller	Weight of Vehicle/ Manipulator and Module	Load per Top Roller	Roller Position	Roller Diameter	Roller Length	Hertz's Stress
mm	kN	kN	kN		mm	mm	MPa
361	43.385	123.872	30.968	top/bottom	80	175	399.2
				inner	80	120	454.3
				outer	80	50	708.6

σ_a=874 MPa

Table 5-3 Load and Design Condition of Actuating Mechanisms

Actuation Mechanism	Requirements	Required Output Load	Possible Output Load
Rotation around Rail	The No. 15C module must be rotated around the rail.	123.5 kN•m	145.5 kN•m
Outer Arm	The module (4.6 tons) must be pushed/pulled.	45.5 kN	75.4 kN
Rotation along Rail	The No. 9 module must be swung toroidally to scan the position.	50 kN•m	50.3 kN•m

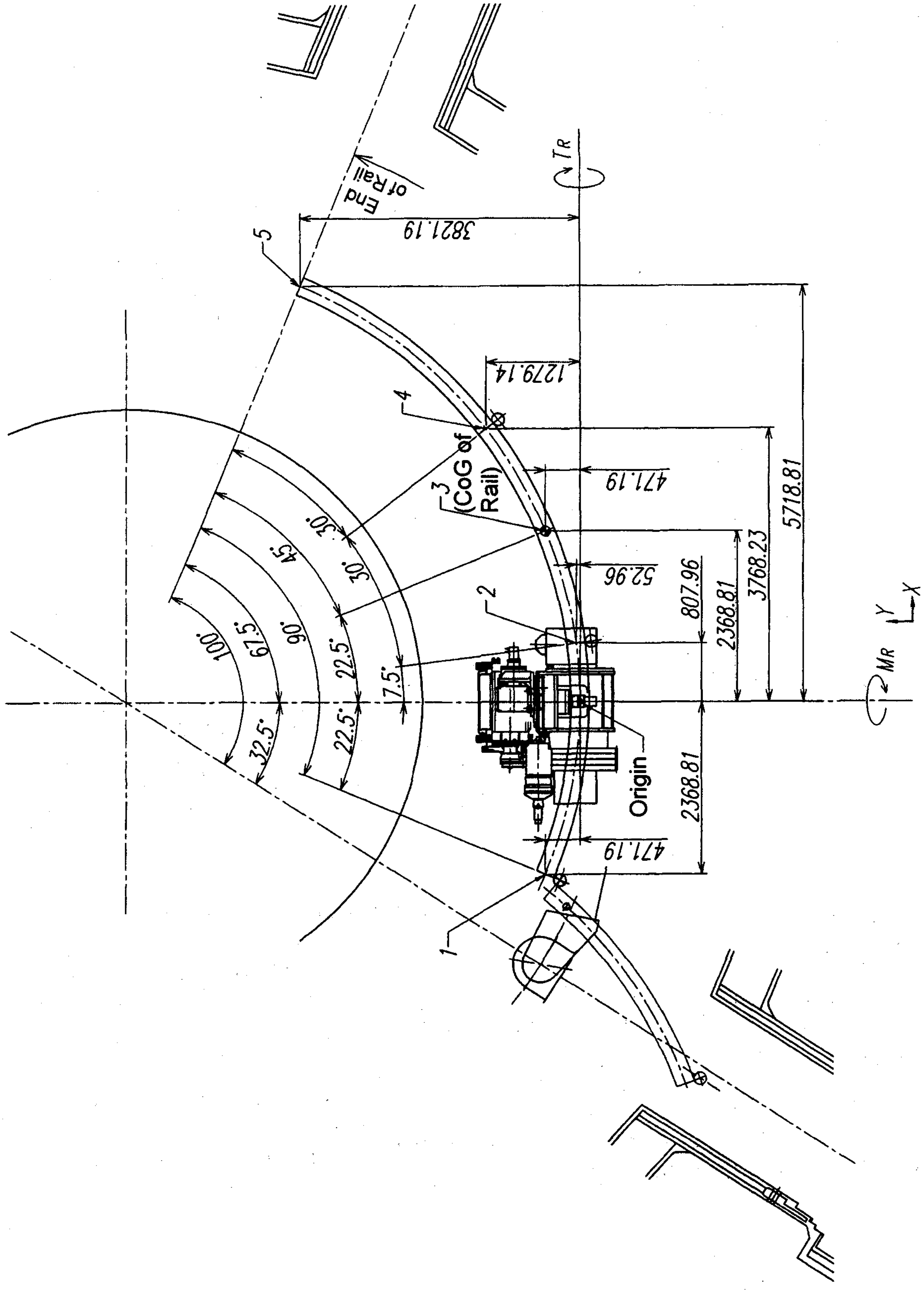

Fig. 5-1 Load Condition of Rail Deployment Phase

6. CONCLUSION

The objective of this report is to study the compactness of the remote handling equipment (a vehicle/manipulator) for the ITER blanket maintenance. In order to avoid the interferences between the blanket and the equipment during blanket replacement in the restricted vacuum vessel, a compact design of the equipment is required. Therefore, the compact design is performed, including kinematic analyses aiming at the reduction of the sizes of the vehicle equipped with a manipulator handling the blanket and the rail for the vehicle traveling in the vacuum vessel.

The compact vehicle/manipulator is designed concentrating on the following points:

- Reduction of the rail size
- Simplification of the guide roller mechanism
- Reduction of the gear diameter for vehicle rotation around the rail

Major approaches for the compact design are as follows:

- Separation of function for guide roller mechanism
- Change of rail material from SM490 to SM570
- Adoption of a double helical gear for the gear for rotation

This compact design could reduce the following dimensions comparing to the 2001 FDR (in brackets):

- Rail size: 400 mm in height, 250 mm in width (500 mm in height, 250 mm in width)
- Offset: of the manipulator center from the rail center: 950 mm (1130 mm)
- Pitch circle diameter of the sector gear: 996.1 mm (1460 mm)
- Output torque of the vehicle rotation mechanism around the rail: 123.5 kN•m (98 kN•m)
- Total weight: 8 ton (11.2 ton)

Feasibility of this design was confirmed by the structural analysis for the rail and the kinematical analysis for replacement of modules. The compact manipulator could replace all the modules without interference.

Based on the proposed compact design of the manipulator, the other components of the vehicle/manipulator system need to be redesigned for compatibility with the proposed design. Major components in the IVT cask, such as the rail connection and deployment systems, have the first priority among them in order to assess feasibility of global design of the vehicle/manipulator system.

ACKNOWLEDGEMENTS

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