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HEAVY MOVABLE STRUCTURES MOVABLE BRIDGES AFFILIATE

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SESSION WORKSHOP NOTES

Session (3-5)
"The Need for Single Failure Proof
Design for the Movable Structures",
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THE NEED FOR SINGLE FAILURE PROOF DESIGN FOR THE MOVABLE STRUCTURES

by
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My firm has been specializing in the design of movable structures for close to thirty years. I must admit that I learned with joy that we finally have the Heavy Movable Structures/Heavy Movable Bridges Association. I am glad to be here.

People have often asked me what kind of engineer I am. Civil, mechanical, electrical? Movable structures. What are they? Do they move intentionally or unintentionally? For many years, it was difficult for me to answer, because our work in movable structures has involved all disciplines. We finally defined our activities as working in a field of structures and machinery for supporting and transporting people and heavy or sensitive loads.

This is a short all-encompassing definition, but sometimes, it may create even more confusion and initially a lengthy explanation has to follow the definition.

Bridges, of course, are the best and maybe the oldest known movable structures. Ancient castles had to have drawbridges crossing the moats and ever since then, movable bridges have had a long history of evolution. There is evidence that the Egyptians had built movable bridges as early as 1355 BC. About 460 BC, the Queen of Babylon built a bridge across the Euphrates with wooden spans so that they could be withdrawn for protection. A marked improvement in the construction of movable brides occurred during the Renaissance and many designs were developed, which served as a base for the modern types.

Bridges, however, were not the only kind of movable structures that go back in history. Rolling towers were required to storm the walls of the castles and the Trojan horse could be certainly classified as a movable structure. Maybe it was even single failure proof.

The fact is, that movable structures can perform a wide variety of functions and they come in many shapes and sizes. The first one I remember seeing in my childhood, was a railroad locomotive turntable. The second was a revolving theater stage. I did not know then that I was to design many unusual movable structures in the years to come.

The design requirements for movable bridges are, to a great extent, defined by experience and by various codes and standards. They provide guidance to the engineer and establish the basic requirements for life expectancy, safety and quality control. But movable structures are not limited to bridges. What, if one wants to move the stadium grandstands, design a movable ceiling over a theater auditorium, develop systems to move nuclear waste, design devices for moving trucks in and out of tall buildings, or create an earthquake bridge for a theme park attraction? These jobs are real, but most of them are one of a kind and the codes and standards for these movable structures are practically not existent. Their performance and safety depends on Engineer's judgement. The ability to exercise this judgement, however, is not always possible, because in commercial construction, the schedule demands and the initial costs often take precedence over the system reliability, maintainability and safety. Furthermore, the importance of design and engineer's responsibility are not always understood by owners.

Let us briefly look at some of these one of a kind movable structures other than bridges.

1. Annular rotating building, designed to carry 1400 persons in six separate rooms around display areas. Dead weight of the rotating ring is about 540,000 lbs. This was the GE Attraction at New York 1964/65 World's Fair.

2. Transport device for nuclear fuel enrichment gas centrifuges was designed to move these heavy, but delicate machines while keeping them out of a wide band of natural frequencies and excessive accelerations.

3. A movable ceiling spans the 100 ft. wide auditorium of Juilliard Theater in the Lincoln Center for the Performing Arts in New York City. It travels up and down to change the acoustical characteristics of the auditorium.

4. A rotating truck lift was designed to move the delivery trucks from street to below street level and speed their loading and unloading where space is valuable.

5. A lift bridge is suspended from traction drive in the opera at the J. F. Kennedy Center in Washington, DC.

6. A design for movable aircraft maintenance platforms provides access to all aircraft tail surfaces.

7. The Metropolitan Opera stage wagon/turntable is designed to create simultaneous horizontal and rotational movement. The 60 ft. by 60 ft., 125,000 pound complex is only 12 inches high, is self-contained and houses all its drive machinery.

While the functional, operational and safety requirements for these systems are entirely different from each other, they are all movable structures. They consist of closely integrated systems of machinery, structures and controls. Some are designed to rotate, some to travel horizontally and others vertically. Some perform all these functions and are even designed to shake. Common to all of them is the fact that for personnel and/or operational safety they are all designed to be <u>single failure proof.</u>

While single failure proof design is mandatory for much of the aerospace and nuclear work, its requirements are not well defined for the movable structures used in other industries, theme parks or in buildings and at the places of public assembly.

There are exceptions. A passenger elevator, for example, is probably the best known single failure proof transportation device. The elevators are designed not to fall if a hoisting cable breaks. In fact, elevators are designed not to fall even if all the hoisting cables break because the independent braking system would engage the guide rails and stop the fall.

In the late fifties and early sixties, there was a rash of deadly building maintenance platform failures in New York. To the best of my recollection, one of the causes was the lack of proper lubrication of the winch worm gear units. Such worm gears are mounted in enclosed housings and even if properly designed or selected, the wear of the gears is difficult to inspect and is often unnoticed until a failure occurs.

It took several accidents before adequate safety codes and regulations were prepared, but now ANSI A120.1 "Safety Requirements for Powered Platforms for Exterior Building Maintenance" establishes strict rules for single failure proof design requirements for this equipment. It can serve as a good reference for those who design cable suspended movable structures.

Thus, while the conservative design reduces the probability of failure, it does not necessarily protect against lack of quality, lack of inspection, or lack of proper maintenance. Furthermore, the detailed designs for many movable structures for buildings are often prepared by fabricators and contractors, based on performance specifications supplied by the architect or the engineer. Because of the competitive nature of construction business, a contractor cannot provide conservative equipment or build a single failure proof system when this is not specified. Therefore, where safety comes into play, the single failure proof design requirements for movable structures have to be clearly defined by engineers and architects. This means that the system must be designed and built so that a malfunction of any one structural, mechanical or electrical component due to misuse, hidden defect, or longtime wear would not create a damaging condition, but would rather, stop the operation of the system and give notice that the fault has to be corrected.

The single-failure-proof principles can be best described by looking at certain specific projects. Whether or not the application of these principles is necessary is an engineering decision that depends on the risk factors involved and on the damage a potential failure could cause.

One simplified example is a gear rack-type lifted structure. Fig. 1 is a schematic underside view of such a lifted structure, which climbs up and down on the fixed gear racks. The lifting system consists of a centrally located motor or motor/reducer unit, connected by shafting to right angle pinion drive gear reducers which in turn are connected to drive pinions through cross-shafting. All machinery is mounted to the underside of the structure. Drive pinions engage the stationary gear racks and are driven by the motor through shafting and gearing to raise or lower the structure by climbing the racks.

The system, as shown, is not single-failure-proof. Failure of a pinion drive gear reducer would cause one end of the structure to fall.

In contrast, the system shown on Fig. 2 employs a single-failure-proof design. In this case, each pinion is driven by a separate self-locking pinion drive gear reducer. Should one of these fail, the additional load would be transferred to the adjacent gear reducer and the lift platform would be held level by three remaining pinions. The drive would jam or make plenty of noise until repaired, but a potentially disastrous accident would be prevented. The failure of one gear rack or pinion would be likewise single-failure-proof for both systems and would not cause the lift platform to fall.

The above description again is a simplified one. Using four self-locking pinion drive gear reducers does not alone make the system safe. All other components must be designed accordingly. The gear racks and pinions, for example, must have sufficient strength for sudden load transfer and the platform framing must be capable of supporting the loads when carried by diagonally opposed gear racks. This, however, does not double the size of the mechanical components because the factors of safety used for normal operating (including fatigue and other considerations) can be reduced for a short emergency period. A thorough engineering evaluation is necessary.

As a further example, a single failure proof design for this lifted structure can be achieved by other means. The lifted structure shown in Fig. 3 has the same drive system as described for the lift in Fig. 1. The difference lies in the guides -- they are placed vertically far apart from each other at both ends of the lift platform. In this case, the structure would be held level by the force couple developed in the guide shoes if a pinion drive gear reducer rails. All components, of course, have to be designed to have adequate strength. This system requires additional depth in the pit to accommodate the guide brackets and thus may be more costly than other solutions.

Single failure proof design is not necessarily limited to prevent the structure from falling or running away. Other operational considerations are equally important.

Recently we designed a drawbridge system for personnel access to simulators. The bridges operate hundreds of cycles per day. One of the single failure proof features is the ability to lower the bridges in case of emergency when all the electrical and hydraulic power fails.

The dry handling system for the spent nuclear fuel shipping cask had to be single failure proof. One of the requirements was to prevent the contaminated fuel storage pool water from escaping to the outside of the plant. All customary precautions were taken, such as double seals, etc. But the final means for safety was simply to make the cask handling system corridor large enough so that if a catastrophic failure would occur, the water would flow from fuel storage pool into the corridor where it would be contained. It would be a mess and require a cleanup, but no contamination would escape the plant.

One of my most serious concerns during my engineering career relates to the moving overhead structures in places of assembly. They often hang over hundreds of people and single failure proof design principles are mostly unknown to their designers. In fact, many of these movable ceilings are designed or specified by consultants, who are not even engineers and who rely on the technical information from manufacturers' sales personnel.

Many years ago when I was working for a manufacturer, one of our projects was the movable acoustical canopy in a major performing arts center concert hall. The specified design relied essentially on one reducer (and probably on one gear tooth) to support 28,000 pounds of plaster and steel above the heads of the performers.

The manufacturer recommended installation of safety holding brakes, but nobody was willing to pay for them. After the system was installed, as specified, additional loads were added to the canopy by the operating personnel until one day the motor failed to raise it. In a way, this was a built in safety feature: The gear reducers and drive train were designed to withstand the stall torque of motor with adequate safety.

The problem was easily overcome by the inventiveness of an engineering firm. They did not research the initial design considerations and designed a counterweight system with a single row of counterweighted cables connected to the center of gravity of the canopy. Then, as time went by, more weight was added and the center of gravity shifted until the counterweights tilted the canopy. More than 60,000 pounds of unknown materials, combined with a questionable array of structural elements, swung merrily through a sweeping arc above the Philharmonic Hall stage and a fast movement of people was observed below.

No problem -- somebody again found a quick remedy how to fix it. More weights were added to the rear of canopy until it was balanced again. Nobody, of course, attempted to find out about the redistribution of loads on the drive machinery. I was very concerned, because I was aware of the initial design details and their shortcomings. It took me two years, after I became the consultant to Lincoln Center, to convince the owner that the canopy was not safe. It was finally dead hung and later removed.

This happened almost 30 years ago. Many similar movable ceilings have been built since and hang over the unsuspecting public.

Should the public be as safe as a window washer, working high above a city on a scaffold, suspended from the top of a building?

The unsuspecting public would not believe that the two situations are even comparable. But the fact is that all hoists lifting the scaffolds have safety brakes, whereas in many places of public assembly the suspended movable overhead structures, weighing tens or hundreds of thousands of pounds, hang over the people and often rely on one gear, one coupling, or one shaft for their support. There is no difference in safety, whether one stands on top of a movable structure or below it.

One simplified version of a simple movable suspended structure is shown on Fig. 4.

The structure shown is suspended by twelve lines, each connected to a drum which, in turn, is supported and driven by a line shaft. Four drums are mounted on each line shaft and a total of three line shafts are used. Bearings and supports are not shown.

The line shafts are connected to each other by cross shafting and driven by a single motor. As an alternate (not shown), each line shaft can be driven individually by separate motors if variable tilted positions are required for the structure. The line shaft system is used only to describe the problem. Many other types of lifting and hoisting systems can, of course, be utilized.

For the purposes of this example, each gear drive (R-1, R-2, R-3) is self locking, the spans between lines 1, 2, 3 are equal and equally loaded.

Case 1

Postulated failure of gear drive R-2

a. The gear drives R-1 and R-3 have to carry the total weight of the structure and experience a 1/3 load increase.

b. The structure has to span from line 1 to line 3 without the intermediate supports at line 2. The span is doubled which causes a fourfold stress increase.

Case 2

Postulated failure of gear drive R-1

a. All the structural weight is transferred to cables on line 2. Because the structure will be balanced about line 2, the cables on line 3 will not carry any load and the load on the gear drive R-2 is tripled.

b. If the load on span 1-2 is even slightly more than on span 2-3, the structure will tilt.

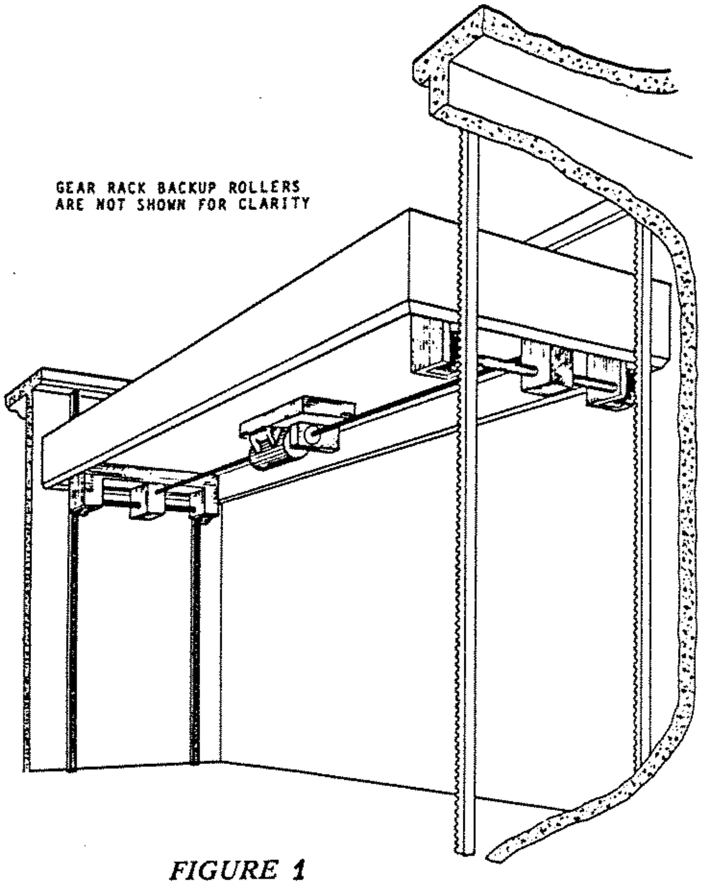
c. The former simple span 1-2 becomes a cantilever and the stresses are increased four times over the original stresses.

Whether the above system is single-failure-proof depends on the strength of the individual components and structural members that carry the increased loads. In the case shown, the machinery experiences a triple load increase and the structure a fourfold increase in stresses. A major increase in the size of the machinery and structural members would be required to make the structure single failure proof. This, however, would not prevent tilting of the structure.

Fig. 5 shows the same structure, but instead there is one gear drive per shaft and each drum is driven by an individual self locking gear reducer. In case of a failure of any one of these, the load transfer is a small one and the related load increase on the adjacent reducers and structure is equally small. A failure of a cable or drum shaft would cause an equally small load transfer. It is quite likely that in this case the engineering analysis would show that the increased loads remain well within the safety factors of the components and only minimal equipment size increases (if any) can provide the required single-failure-proof design with adequate safety. The tilting of the structure is also prevented.

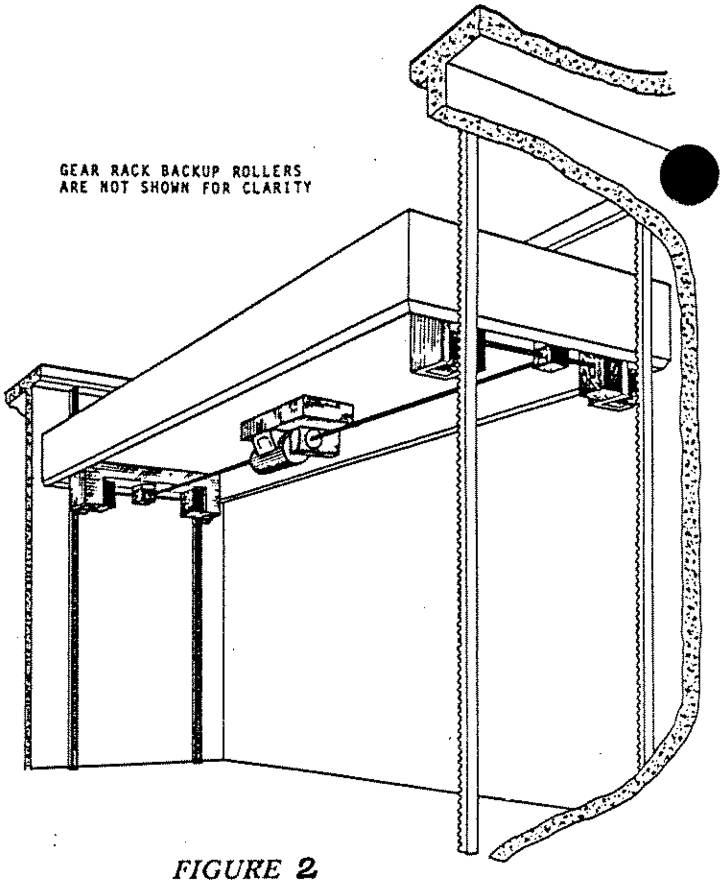
All this seems to be very simple and obvious. For some reason, however, the common sense details of many movable structures are often overlooked. In my opinion this will continue unless some regulations can be adopted and enforced. These regulations should not be restrictive to prevent the engineers from applying their innovative ideas for the design, but they should establish minimum standards for safety leaving the engineer the freedom to choose the means and methods to achieve adequate safety.

While I believe it is almost impossible and impractical to prepare a comprehensive code to cover a wide variety of movable structures, it should be quite simple to establish the basic guidelines and requirements for single failure proof design for movable structures and make it mandatory that a single failure analysis and its description be prepared by a licensed professional engineer and reviewed by appropriate authorities when safety is paramount. I believe, this can be done through the building codes or maybe even through organizations, such as ANSI and others.



GEAR RACK BACKUP ROLLERS
ARE NOT SHOWN FOR CLARITY

FIGURE 1



GEAR RACK BACKUP ROLLERS
ARE NOT SHOWN FOR CLARITY

FIGURE 2

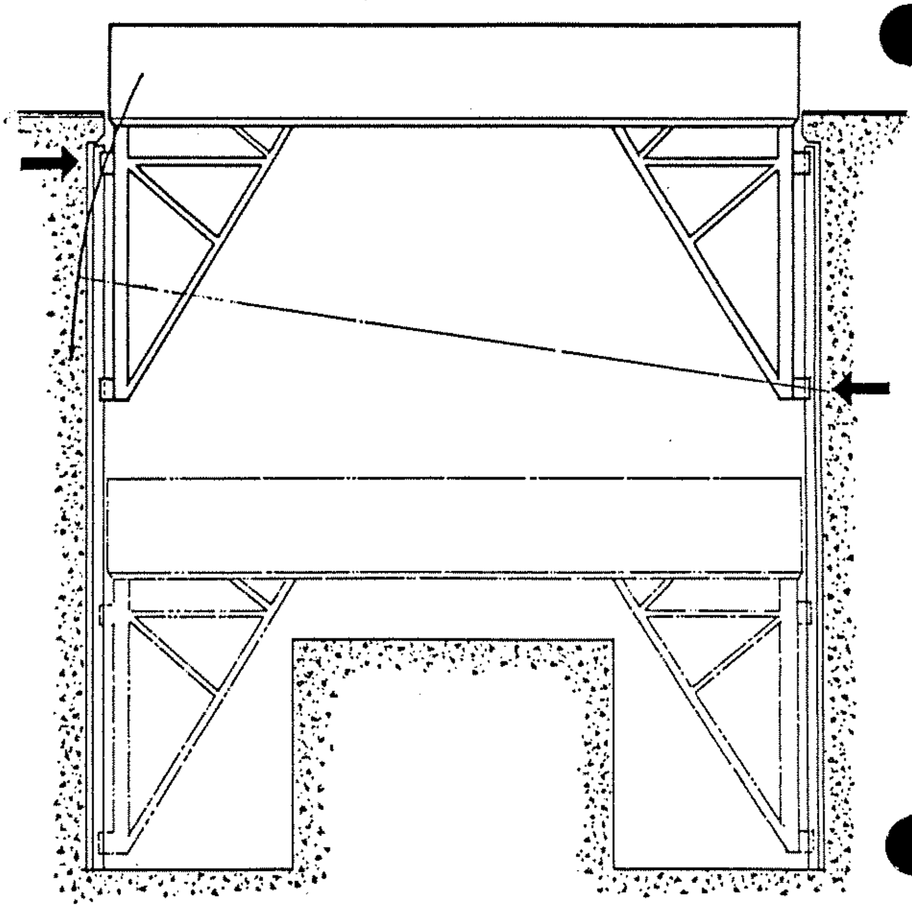
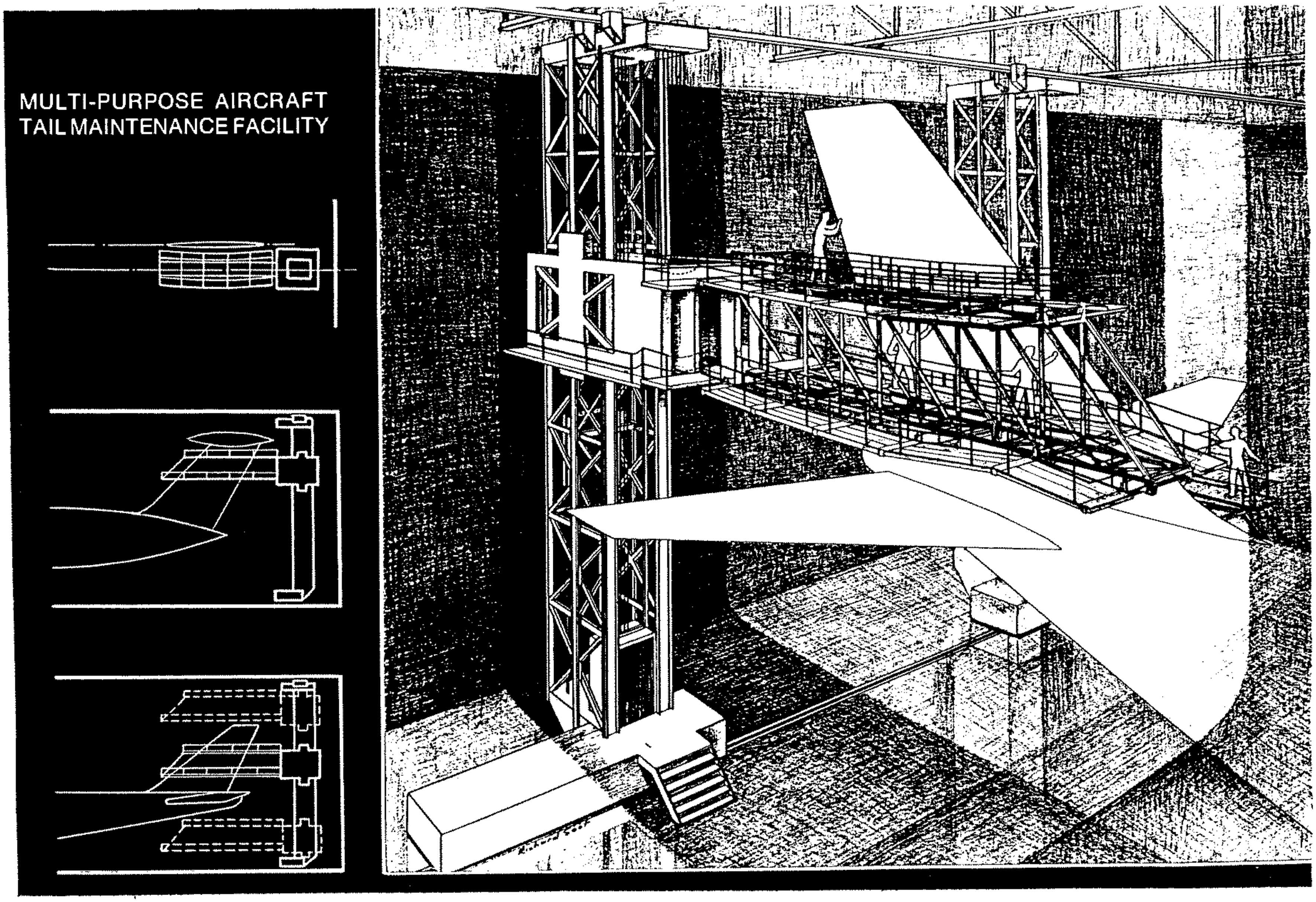
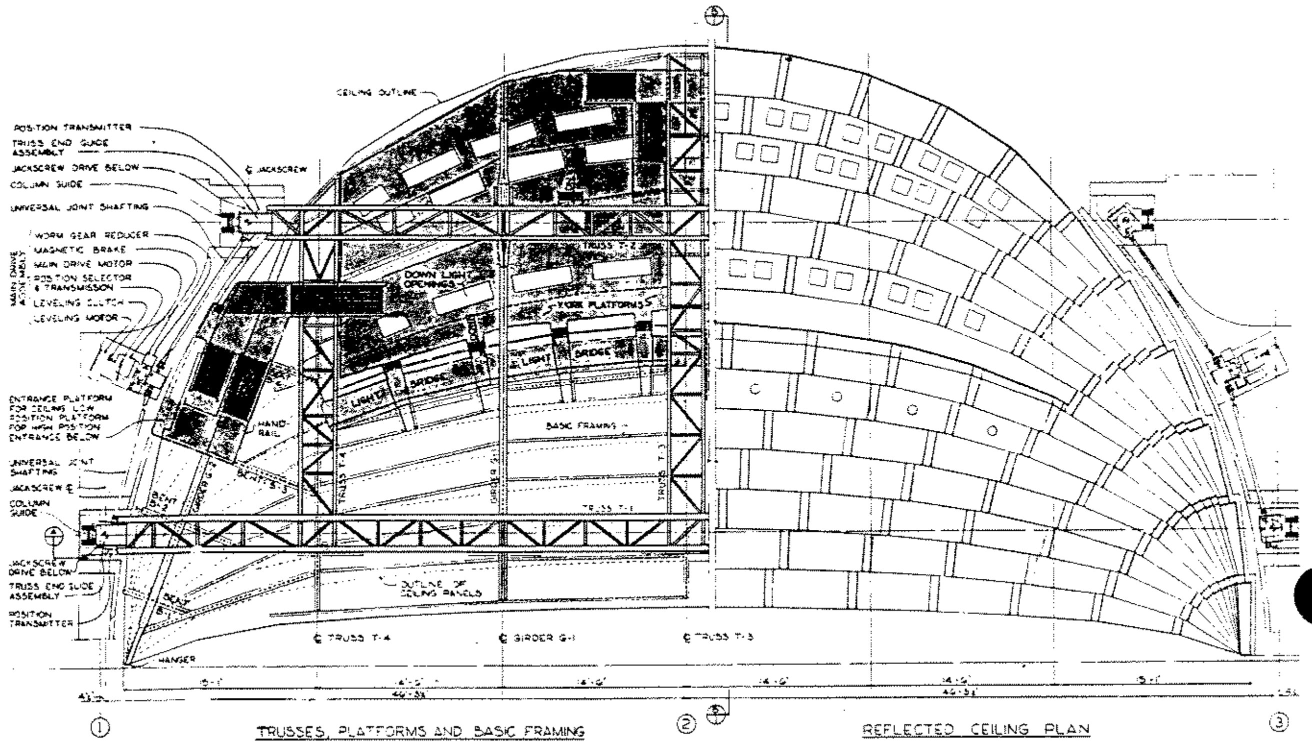


FIGURE 3



Aircraft tail maintenance platforms

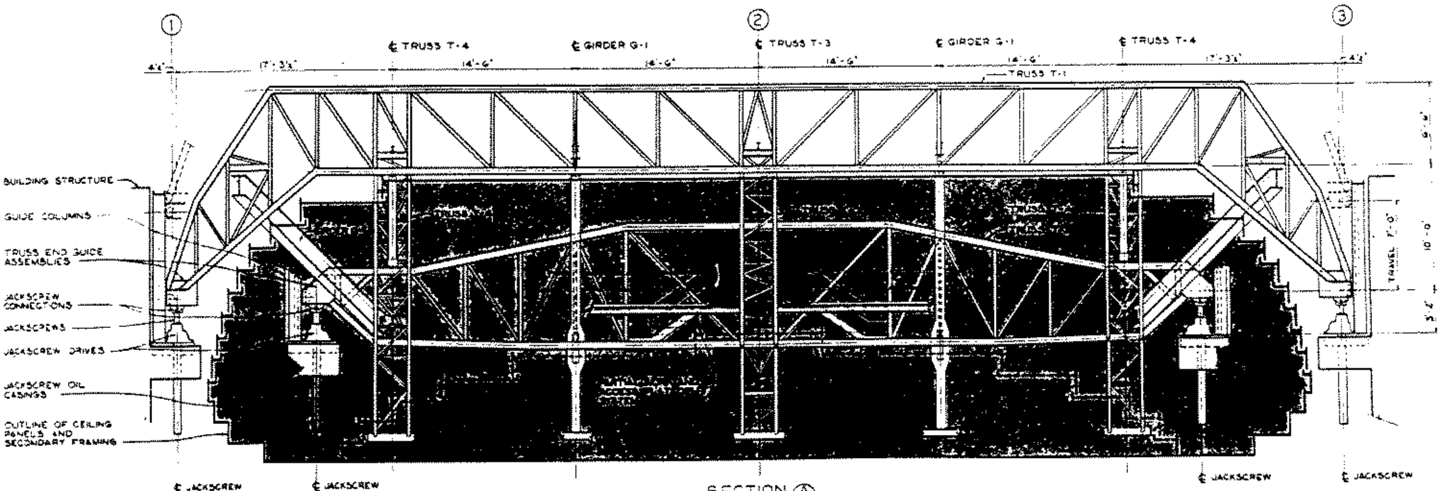
Movable ceiling



TRUSSES, PLATFORMS AND BASIC FRAMING
SECONDARY FRAMING NOT SHOWN

REFLECTED CEILING PLAN

PLAN OF MOVABLE CEILING



SECTION A
SHOWING MAIN TRUSSES, GIRDERS, GUIDES AND JACKSCREW DRIVES

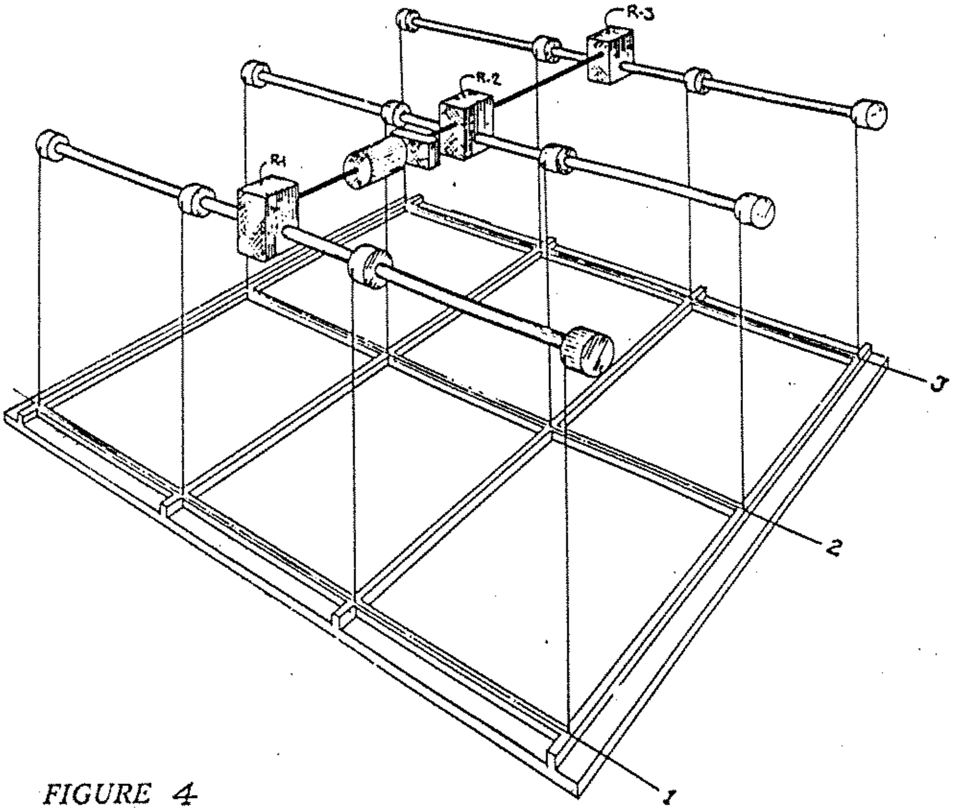


FIGURE 4

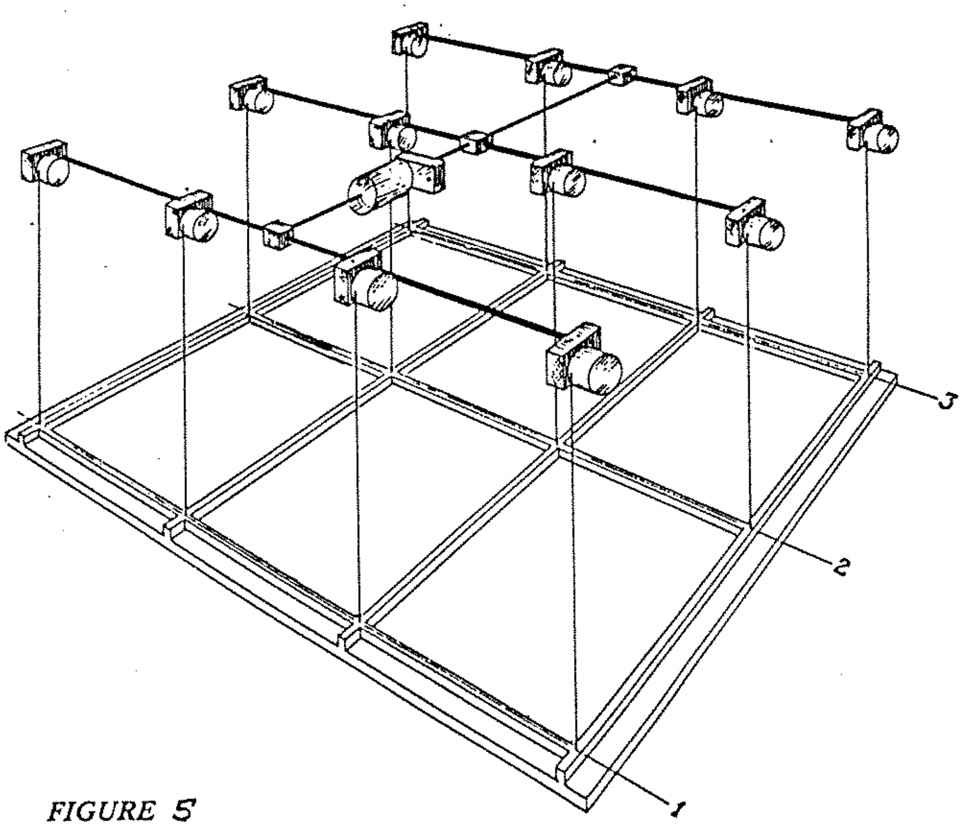
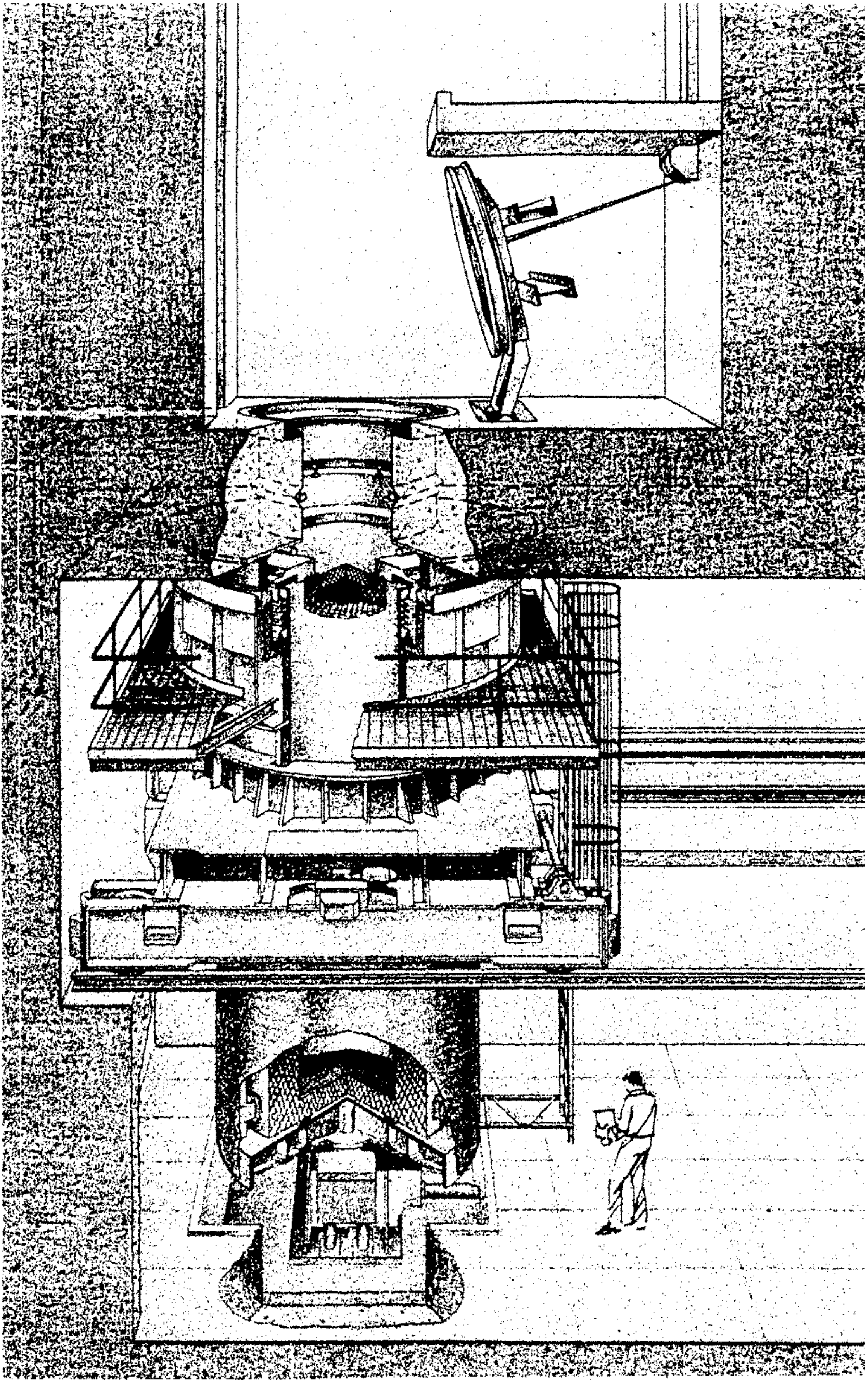
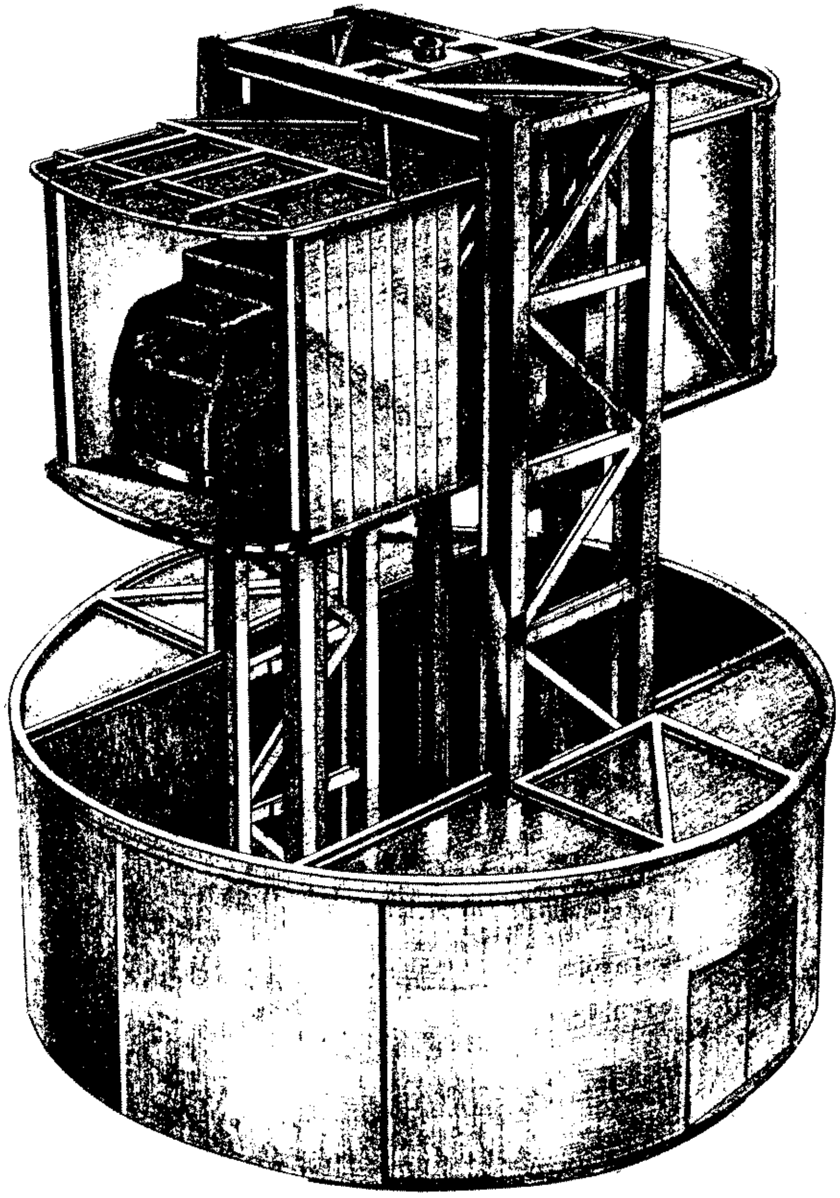


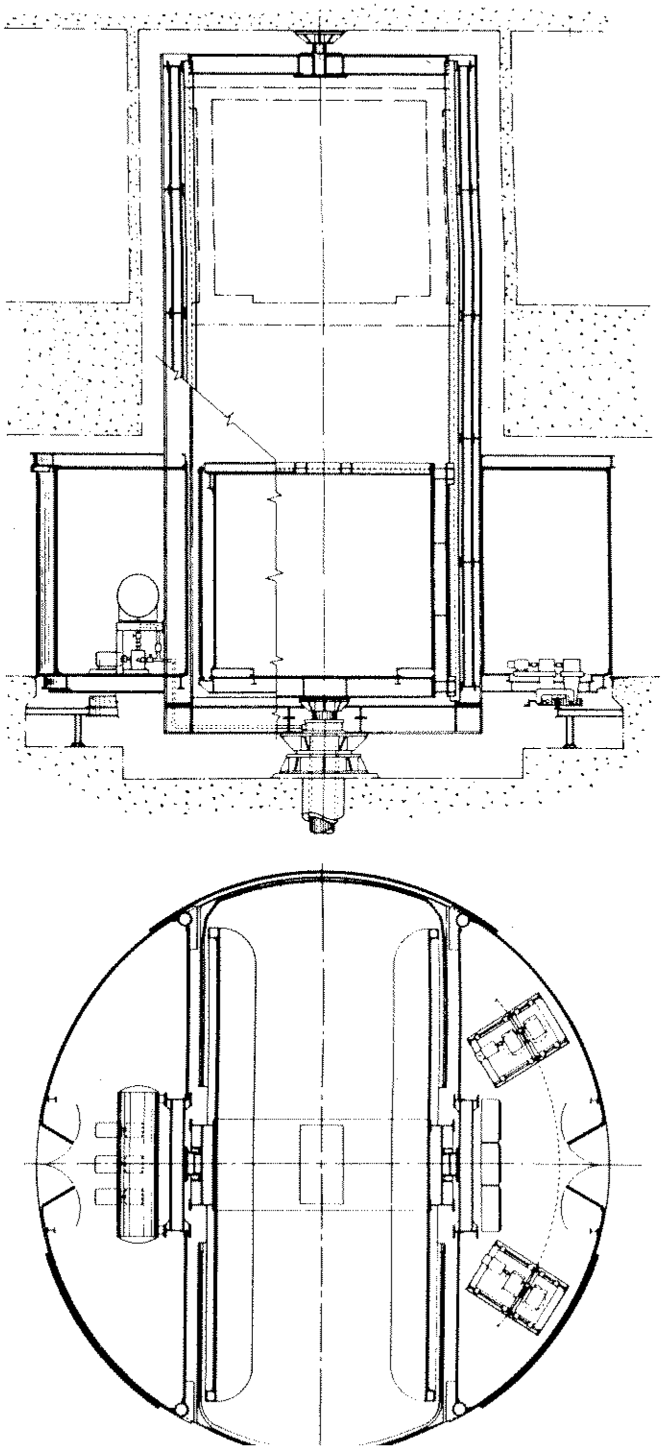
FIGURE 5

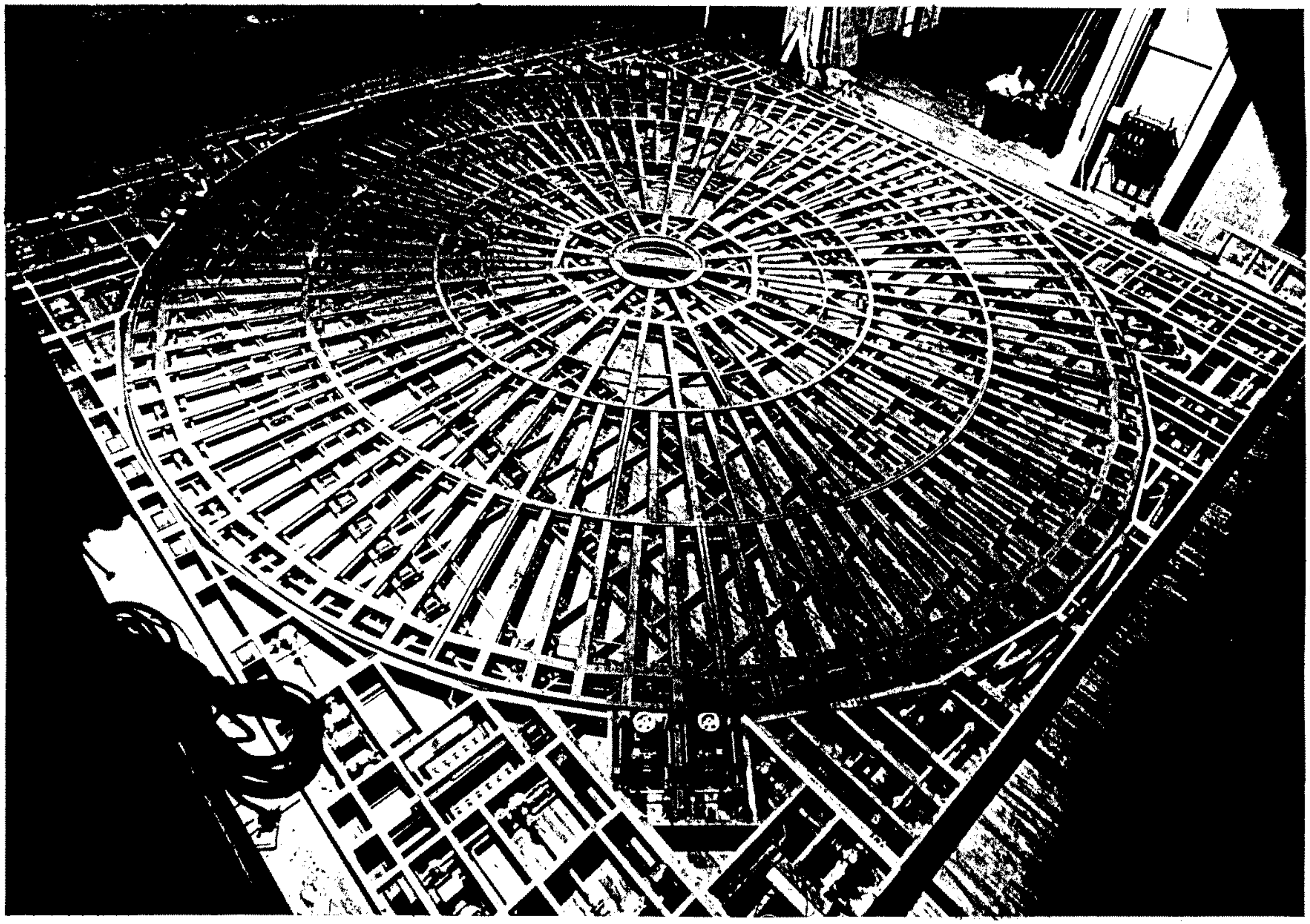


Dry cask handling system



ROTATING TRUCK LIFT





Stage wagon with turntable