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# IN-ORBIT CONSTRUCTION WITH A HELICAL SEAM PIPE MILL

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The challenges of building large structures in space, and in particular a torus habitat, require novel processes. One potential method is to manufacture helical seam (also called spiral) pipe in orbit using a pipe mill. These machines turn rolls of steel or alloy into fully formed, welded and inspected pipe, pressure vessels and silos of various diameters. Pipe mills are highly automated and efficient in a factory environment and are increasingly being used for in-situ repair. By constructing in-orbit (on-orbit assembly) the launch vehicle can supply full payloads of compact, robust rolls of material; and the installation design is less restricted by fairing constraints and modular limitations. The use of a pipe mill is discussed as a possible construction method, for comparison an example design envelope is shown and further pipe mill products are considered.

**Keywords:** In-orbit construction, pipe mill, habitat, torus, rotating wheel space station

## 1. INTRODUCTION

Significant decisions in space exploration to date have been taken over direct versus indirect modes [1], with the former proposing a single launch vehicle powerful enough for the task and the latter advocating some level of assembly in orbit from multiple launches.

The vast majority of installations in space have been lifted in single launches. With the space stations of the Salyut programme, Mir, and culminating in the International Space Station (ISS), far larger installations have been assembled in orbit using modules from multiple launches. However it is still the case that each individual module is limited to the capabilities of the launch vehicle, whilst adding the complexity of in-orbit assembly.

These long missions have allowed us to study the potentially debilitating effects on man of prolonged microgravity. High equipment failure rates have also been experienced from lack of heat convection [2]. In the decades preceding manned missions, many designs intended to mitigate these effects with a rotating wheel habitat to create artificial gravity by reaction to centripetal acceleration [3]. For an interplanetary mission, such as a voyage to Mars, it would be advantageous to provide artificial gravity for the health and wellbeing of the crew.

Without doubt a torus is more difficult to assemble than a monolithic structure, asking the question: how to sub-divide, strengthen and squeeze such an installation through the launch vehicle conduit from earth to orbit? Wernher von Braun sought to address this with several collapsible modules [4]. By the late 1950's his attitude to space station design (e.g. Fig. 1) was "Let's envision a space station and what [it] is made up of, what it can perform and not worry too much about how we would get it up there" [5]. Yet the construction method is key to the feasibility of such a space station, and this challenge requires the development of tools, subject to risk-benefit analysis, of absolute reliability and severe mass limitations. In this discourse an in-orbit construction method is considered to address both monolithic (tubular) and rotating wheel (toroidal) structures.

## 2. HELICAL SEAM PIPE MILLS

A very successful automatic manufacturing technique in terrestrial applications is the helical seam pipe mill, also called a spiral pipe mill. Two-thirds of steel tube production is by welded tube mills [6]. A tool of this efficiency, with high production standards and limited human intervention, is a strong candidate for in-orbit construction. Such a mill could manufacture tubular and toroidal structures from alloy and composites, with dimensions largely independent of the launch vehicle fairing size.

Helical seam pipe mills use rolled steel or alloy that is uncoiled, aligned and rolled by one internal, and a cage of external rollers to create a tube, welded internally and externally and then inspected (ultrasound and X-ray) as part of a continuous process. When one roll is finished another is welded on without interruption and sections may be automatically cut to length. The pipe may also be corrugated.

The pipe dimensions are produced according to:

$$\sin\alpha = \frac{W}{\pi d}$$

Where $\alpha$ is the skelp (strip) feed angle, $W$ is the skelp width and $d$ the tube diameter (minor axis for a torus) as per Fig. 2 [6].

Silos of large diameters, up to 25 m, can currently be manufactured in situ with lightweight equipment. There are also growing developments of construction and repair in demanding environments by helically wrapping pipelines; and internally installing liners underground, such as [7], a technique that might have applications in Martian lava tubes.

## 3. IN-ORBIT CONSTRUCTION

### 3.1 Tubular Products

The simplest form that the helical seam pipe mill can

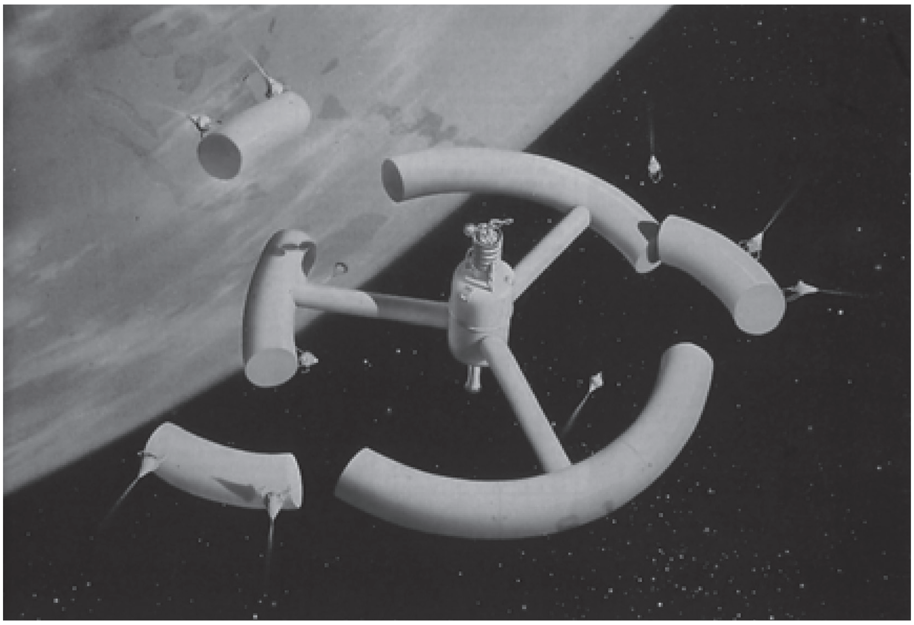

**Fig. 1 von Braun space station.**
**(© Disney 1955)**

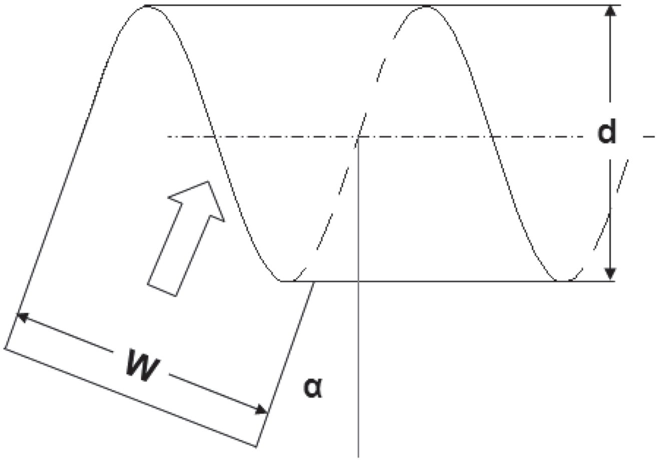

**Fig. 2 Helical pipe.**

manufacture is a tube. An in-orbit tubular build would start with the construction of the mill from modules lifted into orbit.

The mill consists of, say a hex frame larger than tube diameter *d*, with rollers to form helical pipe. This would be assembled by extra-vehicular activity (EVA). Specially prepared alloy and composite rolls, taken to orbit as dense payloads, are lined up to feed the mill. Each is tailored for the job with pre-prepared features and edges to minimise the task in-orbit.

First an inner skin of tubular alloy is rolled and internally and externally welded [8] to create an uninterrupted internal volume. A sensor head follows to inspect the integrity of the weld. This part of the process is largely automated. The mill can be positioned by rotation and translation to any point on the tube by its rollers, and could act like the Mobile Transporter aboard the ISS, carrying a robot arm.

Subsequent passes along the tube can be made adding additional layers, such as carbon fibre for strength. One preferred construction for Micro-Meteoroid Orbital Debris (MMOD) protection is the so-called ‘stuffed Whipple shield’ [9] with a blanket equidistant between two alloy skins. This blanket consists of a ceramic fabric layer (e.g. Nextel) backed by a high-strength fabric layer (e.g. Kevlar), and may also incorporate multi-layer insulation (MLI).

To separate inner and outer skins the mill could apply a helical strip stand-off normal to the skins, resembling a vortex shedding strake on a tall chimney stack. A consequence for the outer skin is that the internal roller would need to be narrower than the inter-strake gap. One possible method of suspending the blanket uses folds in the strake that collapse when compressed by rollers, crimping the blanket on both sides and affording a protective overlap.

By dint of the rollers being set to a larger diameter a second, outer skin can be rolled and welded externally. This seam can be out of phase with the inner for reasons of strength, or rolled with the opposite chirality.

The pipe mill would therefore make several passes over a multi-layer section during construction, the relative rotation dependent upon the changing mass distribution. After the automated processes, the provision of a rotating welding head also allows flanges, frames and supports to be added as required, under human guidance.

### 3.2 Torus Habitat

To create a torus habitat, sinusoidally edged skelp and Z-axis rollers would be used to produce an approximately curved tube, of major diameter *D*. Here the 3D problem is reduced to a single weld point on a continuous seam, rather than a series of discrete processes where the relative positions of all the elements must be co-ordinated. On completion of the structure the interior is loaded with equipment and the ends are joined. Composite decks may be used, or alloy with ribs pinched by the rollers.

Using an automated machine to construct a tested pressure vessel allows EVA activity to be kept to a minimum. Only after the habitat is pressurised would the crew be required to start on the next phase of the construction, namely fitting-out with the installation of equipment. This work would take place in a ‘shirt-sleeve’ environment, at either zero-g for the movement of heavy payload racks, or with artificial gravity for crew comfort.

The mill remains with the installation, the rotating sensor package continually inspecting the exterior of the torus and the mill proper on standby in case patch repairs are required.

### 3.3 Mixed Construction

In reality a mixed, hybrid construction method may be likely, utilising modular and mill methods with alloy and composites. For example two or three equispaced pre-fabricated (‘tin can’) modules could be used as part of the torus at spoke junctions. Such a module can be robustly built and may be fitted with windows, an EVA airlock, pressure doors etc. In the construction phase the mill can be attached to one end of such a module, reducing the weight of the mill.

The tube diameter could be large enough to be the entire installation (space station or spacecraft), a walkway of say 3 m in diameter, or merely a strength member, to which inflatable modules are attached. Similarly different tube diameter segments may be combined to provide large habitat volumes and a continuous corridor through inflatable greenhouses etc.

## 4. EXAMPLE DESIGN ENVELOPES

The straightforward relationship between area and volume for a torus is shown in Fig. 3 for various tube diameters *d* (minor axis). The designer may operate within the shaded design envelopes, limited by rate of rotation and tangential velocity for crew adaptability to artificial gravity [10], providing a free hand in terms of mass, tube and torus diameter, deck area and pressurised volume. However pre-fabricated structures are here limited to *d* 4.5 m by launch vehicle fairings, and inflatable designs [11] to an expanded diameter of 6.7 m.

Also shown in Fig. 3, as points, are three proposed space stations: Potočnik’s of 1929 [3], von Braun’s of 1952 and an octagon made from Shuttle External Tanks of the type described in reference [12] from the 1990’s.

The mass of an example design could be reduced for the same volume by selecting a larger tube diameter *d*, putting us well into the mill design envelope. If this were as large a diameter as our chosen crew adaptability criteria permits, then there is a mass saving of about a third when hoop stress is taken into account. Alternatively, the example could be translated to the boundary for the same mass, again making an adjustment for hoop stress, increasing the internal volume by a half.

## 5. ADVANTAGES & APPLICATIONS

The advantages of the mill design over the modular (pre-fabricated or inflatable) designs are:

i) A larger volume is possible for a given mass, less the mass of the mill itself

ii) Installation components can exceed payload dimensions

iii) Large diameter shields can be added, bringing weight savings without impacting on the internal volume

iv) The installation can be designed for a low-g environment and will be lighter than modules that must withstand the rigours of launch

v) Fuller utilisation of each lift can be achieved closer to the average payload density of the launch vehicle. Using high density rolls 95% of a typical payload volume is free for a trade-off with lower density materials, such as carbon fibre decks and interiors

vi) The material can be conveniently divided into compact mass units. In particular Reusable Launch Vehicles (RLV), such as spaceplanes, promise to dramatically reduce the cost per kg to Low Earth Orbit (LEO), but the emphasis may be on payload mass with volume curtailed by hypersonic aerodynamics and structural considerations, or insist on g-hardened payloads

vii) A single automated process minimises EVA

Various tests can be made during construction, including weld inspections, pressure tests, activation of the monitoring system and EVA inspections. However a key deficiency with in-orbit construction is the limited test regime. Installation modules are among the most thoroughly tested structures made by man and this would be impossible to approach in orbit.

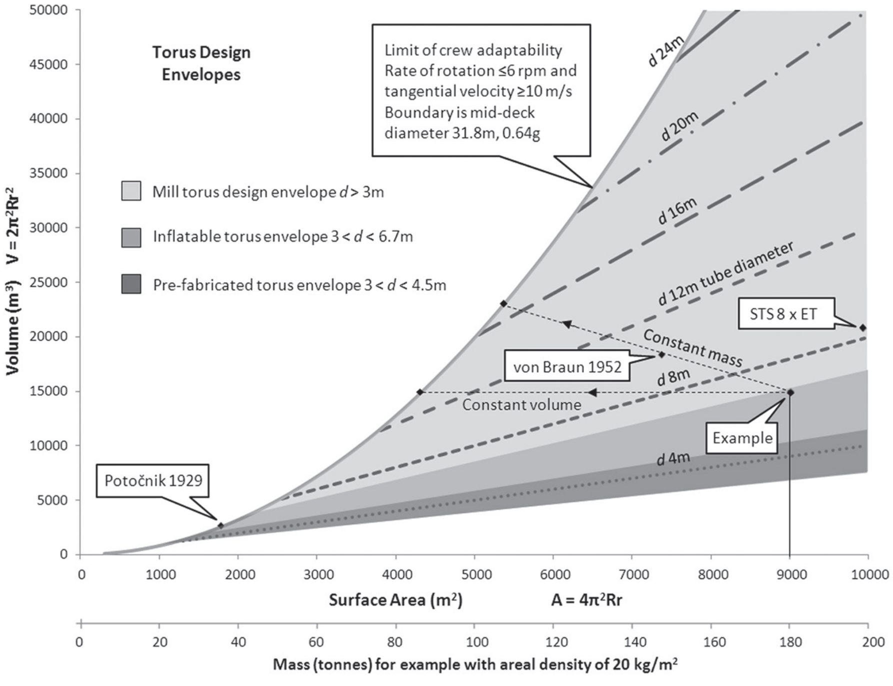

**Fig. 3 Simplified Torus design envelopes.**

A modular torus is less efficient because:

i) Multiple cylindrical modules result in a pseudo-torus of chords with varying centripetal accelerations

ii) Such a shape creates certain structural challenges over a continuous torus. Additional mass would be required to connect or flange each module together, without adding to the volume of the habitat

iii) Inflatable modules are typically necked to a core making for a lower volumetric efficiency, particularly if a curved interior is fitted

In short, the modular design envelopes and lifting plans are restrictive.

Almost any construction may benefit from tubular products at different diameters, such as:

i) Cylindrical housings or more complicated, non-circular cross-sections, and toroids

ii) 'Double-helix' sections with large, diamond-shaped, greenhouse windows

iii) Spars, spokes, frames and trusses including latticework for photovoltaic arrays

iv) Tanks for fluids and propellants

v) Pipework, heat pipes, fin tubes, heat exchangers; and plastic 'welded' conduits for internal applications

vi) Adding one or more large diameter Whipple shields to a pre-fabricated habitat. This is among the more pragmatic options, using a thoroughly tested module made to the limits of the launch vehicle, and adding large diameter shielding in orbit

vii) A large vessel could be made to enclose satellites for manned servicing, or even for asteroid capture

On the surface of the Moon or Mars the mill could manufacture many of the components of a base, such as:

viii) Habitats and interconnecting walkways buttressed with regolith

ix) 'Polytunnels' as greenhouses, possibly with a reinforcing wire in the seam

x) Well casings, pipelines, piles, silos and tanks for the storage of In Situ Resource Utilisation (ISRU) products

xi) Slender spars fitted with terminations or flattened and drilled in order to construct a geodesic framework for spheres, domes or parabolic reflectors

xii) A pressurised section could be produced as a land vehicle cab, fitted to a chassis

xiii) The mill could make the cylinder and blade of a continuous process cement mixer, and spend its last weeks turning this on its rollers to produce hundreds of tonnes of concrete (or lunarcrete, 'regocrete' etc)

These structures can be delivered 'flat-packed' as compact and robust alloy and composite rolls to the surface of the planet.

## 6. CONCLUSIONS

Central to mankind's progress has been the development of tools that have allowed us to prosper in diverse environments. Construction tools are required for large installations, including those that may be suitable for prolonged manned missions such as voyages to Mars.

Ideally an installation design would not be limited by fairing dimensions, nor by the stresses of launch; but be constructed to an uncompromised design for a microgravity environment. In addition a rotating wheel installation (space station or spacecraft) is an attractive option to create artificial gravity. However, such a structure is difficult to construct from modules. Automated pipe mills work well on Earth but an in-orbit helical seam pipe mill would have to deliver a faultless product.

A wide variety of tubular products could be manufactured by an effective construction robot like a pipe mill, enabling large design envelopes. Chief amongst these products, efficient toroids can be constructed to make large volume habitats with artificial gravity.

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