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COLLECTING COMETARY SOIL SAMPLES ? DEVELOPMENT OF THE ROSETTA SAMPLE ACQUISITION SYSTEM

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ABSTRACT

In the reference scenario of the ROSETTA CNRS mission, the Sample Acquisition System is mounted on the Comet Lander. Its tasks are to acquire three kinds of cometary samples and to transfer them to the Earth Return Capsule. Operations are to be performed in vacuum and microgravity, on a probably rough and dusty surface, in a largely unknown material, at temperatures in the order of 100 K.

The concept and operation of the Sample Acquisition System are presented. The design of the prototype corer and surface sampling tool, and of the equipment for testing them at cryogenic temperatures in ambient conditions and in vacuum in various materials representing cometary soil, are described. Results of recent preliminary tests performed in low temperature thermal vacuum in a cometary analogue ice-dust mixture are provided.

INTRODUCTION

The goal of the ROSETTA Comet-Nucleus Sample-Return (CNSR) Mission, is to send an unmanned spacecraft to a comet, to collect and bring back to the Earth samples of cometary material for further laboratory investigations. The analysis of this material will constitute a fundamental step towards understanding the early evolutionary stages of the Solar System.

The **Sample Acquisition System (SAS)** is to be mounted on the lower part of the **Comet Lander**, together with the Anchoring Subsystem. SAS's tasks are first to anchor the Lander to the Comet, then to acquire **three kinds of cometary samples** and transfer them to the **Earth Return Capsule (ERC)** attached to the Return Carrier (the anchored Lander will eventually be abandoned on the Comet). The SAS is primarily made up of : a **coring tool**, a **shovelling tool**, an **external cutting device**, a **manipulator arm**, the associated three **anchoring systems** and the control electronics. Fig. 1 shows the anchored spacecraft with an earlier SAS concept (inset, from ref. 7), and sketches the present design concept.

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GENERAL ROSETTA REQUIREMENTS

Based on the results of Halley and other comet missions, there is a general agreement that cometary matter consists of volatile and non-volatile components and that the bulk composition and the physical properties of cometary material change spatially throughout the comet and its nucleus. For these reasons, three different types of sample are considered essential in order to obtain the optimum information about the comet nucleus :

1. A **core sample** : this to be a continuous sample taken from the surface of the nucleus down to a depth of at least 1 m (goal 3 m); it should provide the interrelation between volatile and refractory compounds in the comet. This sample should be subdivided and stored in separate segments, preserving also its coarse stratigraphy.

2. A **volatile sample** : this is to be taken from a location where the most volatile components can be expected, i.e. from the bottom of the core sample hole (it may be the lower part of the core sample). To retain these components, the sample should be stored in a totally sealed container.

3. A **surface sample** : this is to be collected from one or more locations at the surface of the nucleus. This sample is intended for studies of the refractory carbonaceous and inorganic compounds.

The Sample Acquisition System is designed for the minimum scientific coring depth requirement of 1 m, whilst operating under the following constraints :

- **Environmental (comet surface at 5 AU)** : milligravity, vacuum, surface temperature from 100 to 150 K; soil compressive strength ranging from 10^{-4} to 100 MPa ; soil density from 0.05 to 2 g/cm^3 (dust mantle) and from 0.1 to 1.5 g/cm^3 below. Composition: ca. 80 % H_2O (ice), remainder inorganic and organic (volatile) materials (ref. 3).

- **Scientific** : acquire nominally 1 m core, diameter 100 mm; mass 15 kg of core/volatile sample, 5 kg of surface sample, including loose hard pieces, max. size 5 cm; minimize perturbation and contamination : limit sample temperature increase to 10 K; seal volatile sample; sample compression allowed.

- **System and engineering** : one core hole minimum; acquire sample on a rough surface, 0.5 m above or under the level of the landing pads; max. storage length for 100 mm dia. core segments and surface sample containers : 0.6 m, dia. ca. 140 mm; max. electrical power 100 W, torque 100 Nm, vertical thrust 100 N. (ref. 4). Mass and size budget goal: 100 kg, 1 m^3.

- **Anchoring** : react with margins in maximum sampling thrust and forces (i.e. typically 300 N per anchor).

One of the greatest difficulties is that the physical properties of the cometary soil are not well-known, and therefore a very wide range of possible values must be considered : the hardness ranges over 6 orders of magnitude from that of soft snow's to that of a medium-hard rock (tuff). This extreme hardness, scientifically foreseen for loose pieces only, has been taken as a development goal : the spacecraft has to be anchored and a single corer needs to operate in the hardest soil. As the spacecraft can only provide limited power and thrust (unusually low for rock-like material), this combination of hard soil, relatively large core and limited resources presents the most challenging design constraint.

SAMPLING ACQUISITION SYSTEM CONCEPT AND OPERATIONS

The Sampling Acquisition System (SAS) has to provide the following functions :

* anchoring of the spacecraft to the comet soil;
* collecting of core, volatile and surface samples;
* handling of samples in order to store them in the Earth re-entry capsule.

To ensure maximum simplicity and reliability, the essential functions have been assigned to dedicated mechanisms, in particular that for coring, which is the most demanding sampling function.

Core Sampling Subsystems, Description and Operations

The initial configuration from which all subsystems are deployed is their upper position, required at comet landing, to avoid collision of lowest parts such as the drill bit with the highest foreseen surface irregularities at the landing site. This may also represent a launch mounting position, which can be maintained until after landing.

The functions and operations of the subsystems necessary to acquire a core sample are best described with reference to the schematic of Fig. 1. : it shows an intermediate position where several components have already been disconnected

The **corer rod** is composed of the **drill bit (1)** fixed to the **torque tube (2)**, whose **helical augers** ensure chip removal. The corer rod is connected to the **main rotary joint (10)** and encloses the **core canister (8)** whose bottom **shutter valves (4)** are open. At the start, the **support table (5)** is lowered by the **secondary linear joint (3)**, and stopped when the drill bit reaches the surface, after a maximum descent of 1 m. The main rotary joint provides torque and rotates the corer rod only : the core canister does not turn with the torque tube (to minimize mechanical or thermal disturbances on the core sample which penetrates and fills it, e.g. twisting or temperature increase due to friction). The **main linear joint (12)** provides downwards thrust and controls the advance of the corer ; its stroke allows a maximum coring depth of 1 m.

When this lower coring position is reached, rotation is still maintained, and the inner systems are operated sequentially. First, the spherical sectors of the shutter valves (4) are closed to perform the core bottom sectioning (a detailed description of the bottom shutter subsystem follows). The shutter valves eventually close the core canister. Rotation is then stopped, and the **separable link (9)** disconnects the torque tube (2) from its actuator (10). The closed core canister is lifted alone, the drill rod being left in the soil (possibly spring-latched on the support table). Fig. 1 illustrates the end of this stage, where the sample-filled core canister is completely extracted.

Core segmentation and handling operations then proceed as follows : the **ancillary rotary joint (11)** positions the core canister sideways in the **gripper (6)** which closes its claws. **Sawing disks** of the **external cutting device (7)** are rotated; facing the **middle position to be cut(14)**, they translate towards the canister and cut it with its core sample. The joint (11) rotates the separated assembly to place the upper canister segment above a **first cap (16)**, into which it is lowered and engaged by action of the joint (12) - (care is required at this stage, as both canister ends remain open momentarily, while containing loosely restrained core samples; this sequence, with a short critical path, is acceptable in microgravity).

The **manipulator arm** (similar to the one shown in Fig.1) grasps a **second cap (15)**; after retraction of the saw disks, it closes the upper end of the lowest canister segment, grasps the whole lower sample and, with gripper released, it transports and stores it into the ERC - (the core sample containing volatile compounds is then stored first in the capsule).

Similar operations are performed on the upper sample segment: displacement by actions of joints (12) and (10) with its **upper section to be cut (13)** facing disks (7), capture by (6), cutting, top closing by a **third cap (17)**, and finally storage in the ERC - (this second sample contains core with some crust at the top).

Surface Sampling

The surface tool (similar to the one of Fig. 3) is driven by the manipulator arm. It is composed of a fixed **outer tube** and an inner **helical screw** with a cutting blade at the bottom, which rotates until the tube is filled with chips and loose pebbles. It is foreseen to cap it and disconnect its drive before storage in the ERC.

The use of brushless DC or stepper motors is generally foreseen for all relevant subsystems, most linear and rotary joints being provided with a brake and a position encoder.

It can be noted that tasks in the core sample acquisition sequence are performed by a succession of well separated operations of dedicated mechanisms. The only exception is the manipulator arm : this complex subsystem is used for handling and manipulation, but is also essential for surface sampling. It requires 7 degrees of freedom, and complex joints. As it has the additional benefit of being available for assisting in eventual recovery strategies, this dexterous item could not be easily replaced by a set of simpler mechanisms.

Mass and Power System Budgets

The provisional mass budget for a SAS coring to 1 m depth is 159 kg, without margins, composed essentially of 110 kg for the sampling systems (structure and actuators, including 19 kg of tools (corer : 12 kg; surface tool : 7 kg) and 40 kg for the manipulator arm. 30 kg for the anchoring subsystem (i.e. 3 anchors, each with their deployment and lateral actuation devices) are also included in this budget.

The maximum power budget is 202 W, bearing in mind that operations are non-simultaneous : coring (109 - 202 W), external cutting (20 W), surface tool (125 - 155 W) and handling (105 W).

The testing program will allow refinement of these figures, which represent approximately twice the mass and power budget goals (100 kg, 100 W) for a nominal core diameter of 100 mm. If necessary to achieve compatibility with mission budgets, the present 100 mm core diameter can be scaled down to approximately 70 mm.

PROTOTYPE CORER AND SURFACE TOOLS

A prototyping activity has been started in order to verify the design feasibility of critical subsystems by testing, and to demonstrate the ability to collect different types of materials, ranging from snow to tuff, under severe environmental conditions, i.e. vacuum and -180 C (ca. 90 K, or boiling temperature of liquid nitrogen (LN_2)).

Currently under development are :

* the coring tool;
* the surface tool;
* the external cutting device;
* the anchors.

The core canister extraction and other further operations are not yet modelled. No special motor development is included in the programme at this stage. The manufactured prototype tools are only representative of the samples and other main outer tool dimensions. In accordance with the test objectives, they are not otherwise mass and material representative, as they are mostly manufactured from stainless steel AISI 304, instead of aluminium alloy 7075. Tubes are thicker than required, to allow testing for a wider range of forces and torques with these development models.

Corer Tool Prototype Description

The corer tool prototype (Fig. 2) is mainly composed of :

- the torque tube;
- the drill bit (Fig. 2 d);
- the core canister;
- the shutter valves (Figs. 2 b,c and e);
- the shutter mechanism (Fig. 2 a).

The **torque tube** transmits the torque and the thrust from the actuators to the drill bit, and torque to the shutter valves. Its outer surface and augers are covered with a thick PTFE coating (EMRALON 333).

The "multistep" **drill bit** (Fig. 2 d) cuts the soil in an area of ca. 100 cm^2 (OD 150, ID 100 mm) by means of twelve **polycrystalline diamond (PCD) cutters.** The cutters are positioned at three different levels or "steps" to allow a gradual cutting action. There are two pairs of cutters at each step with a slight overlap between their cutting envelopes. They are brazed onto their stainless steel support by a silver/copper alloy that is suitable for use at low temperature. Each cutter has a negative (apparent) rake angle of 10 deg. and a relief angle of 15 deg., and a cutting edge of either 3.5 or 4.5 mm.

The **core canister** is the thin inner tube that contains the sample during the sample extraction and handling phase, and which is later sectioned and returned with the samples. The shutter valves are attached to its lower end.

The **shutter valves** (cf. figs. 2 b, c and e) sever the core sample when the desired depth is reached. They are two pivoting spherical sectors which may rotate through 60 deg. from open to closed position around a pivot radial to the corer axis. Four PCD cutters are brazed onto the closing edges, as for the drill bit. The **valve pivots** are part of an intermediate **mobile collar**, itself linked by a rotary joint to the bottom of the canister around which it turns freely. **Keys** on the collar engage opposite slots inside the torque tube, which drives the open valves, and transmits torque to them when they start closing. Closure is commanded by the shutter mechanism linked to the shutter valves.

The **shutter mechanism** is located in the upper part of the corer tool. In the concept illustrated by Fig 2 a, two **long rods** of ca. 1 m are connected to a **linkage** of the shutter valves and at the top to a **threaded sliding nut** with keys, which can slide inside the torque tube. A **driving screw** inside this nut is the rotor of a **motor**, normally not powered and turning freely. When the motor is activated, a differential rotational speed between the torque tube and the driving screw occurs, which lifts the sliding nut, pulling the rods and consequently closing the shutter valves. It can be noted that the rods will later be sectioned with the sample canister.

For a cutting thrust of 20 N on each shutter edge (worst-soil case), the maximum rod closing force is 120 N (at start of closure); the power required to pull the rods is only 12 W, which adds to the cutting power provided by the main rotary actuator (comparatively lower for bottom cutting than the one required for drilling).

<u>Surface Tool</u>

The aim of the prototype surface tool (Fig. 3) is to demonstrate the collection of soft and medium hard materials, with superficial layer of dust and harder grains, under various environmental condition. It is sized for the collection of grains with diameters of up to 5 cm. The surface tool consists primarily of :

* a fixed outer tube;
* a rotating inner screw, with double helix;
* a double cutting edge;
* a fill sensor;
* a motor and gear box drive unit.

The collection function is performed with the combined action of the rotating **helical screw**, which allows lifting of the cut material, and of the static **outer tube** (OD 140 mm), which provides storage for the sample.

The helical screw is made by welding an helicoidal structure onto a shaft. It transmits the torque and the thrust to the cutting edge. To avoid jamming while the material is transported, the screw pitch of ca. 130 mm is slightly increased upwards. The **cutting edge** is composed of a conical support structure with a series of ceramic (WIDIA) cutters, brazed onto the support. A spike made of the same ceramic provides centring action at soil contact. The **fill sensor** stops the motor when the outer tube is full. It is positioned in the upper part of the outer tube and is composed of two springs connected with an electrical contact and a plate. When the material reaches the plate, the closure of the electrical contact signals the motor to stop. The **motor and gear box** system comprizes a 750 W DC motor, deliberately oversized for testing purposes. It is a customized item derived from a standard model with some modifications in order to work in the hostile test conditions (i.e. vacuum at -180 C). The gearbox has a 1:4 ratio. The motor axis is parallel to that of the helix for compactness.

Selection of Materials and Lubricants

All the materials used for the prototypes are either space qualified or able to withstand space environments, including very low working temperatures. On-ground cryogenic applications have been taken into account during the material selection process. Major attention has been paid to tribology during the prototype design phase due to the environmental testing conditions (vacuum and -180 C/ 90 K). Since the lowest temperature limit of any liquid lubricant is about -70 C, dry lubrication is required. Duty cycle and components considerations led to the choice of MoS_2 for ball bearings and of PTFE films or VESPEL for sliding parts. A thick PTFE coating coats the corer augers and surface-tool helix, to provide both efficient tool penetration and chip transport, and to resist abrasion.

PRELIMINARY TESTS ON CRITICAL CORER COMPONENTS

To assess the corer tool's performance for the anticipated range of comet soil properties and the environmental conditions expected (vacuum and very low temperature, 100-150 K), series of gradually more complex preliminary tests were performed, to determine the behaviour of some critical components.

Model materials were, from softer to harder, porous ice, Cometary Analogue Material(s) (CAMs, essentially LN_2-sprayed ice/Olivine dust mixtures), compact ice and natural Ettringer tuff (medium-hard rock with harder inclusions).

Corer bits and shutter mechanisms were manufactured and tested to assess first the adequacy of the cutting technology and then select the most suitable design, providing low cutting power and proper "dry chip removal", i.e. without the assistance of any cutting and chip transportation fluid.

Ambient and Low Temperature Rig and Corer Tests

An **early test rig** using an industrial power drill on a sliding carriage was first used (Fig.4); a constant thrust was imposed by imbalanced counterweight. The rig was instrumented to measure drilling torque and advance.

Up to nine **"single step" drill bits** with different types and geometries of cutters (various tungsten carbide, impregnated and polycristalline diamond) were subjected to screening tests on tuff under ambient conditions before selecting a **multistep drill bit** with polycristalline diamond cutters and specifying its final design (Fig. 3 a).

Tests were performed at ambient temperature on tuff and at -25 C on tuff, ice and ice-sand mixture. A number of problems and difficulties were encountered, mainly related to dry chip removal. Test on ice showed some problems due to increased temperature, which changes the water phase from solid to liquid, and vice versa, resulting in ice production on the auger, inducing rapid chip clogging and stopping drill penetration.

Despite these initial problems, it was decided to pursue tests in conditions more representative of the cometary one's, at **-180 C** (LN_2), but still at **ambient nitrogen pressure.** Tests on ice, tuff and CAMs (shown in Fig. 4) demonstrated **successful coring performance** of the multistep drill bit (cf. Table 1) under these otherwise more demanding conditions : the average hardness of the tuff rock had noticeably increased above the maximum specified value. Temperature elevation of the drill bit was in the order of 30 C max. for this harder material.

The **shutter valves** were tested at component level in association with the drill bit and corer with a **simplified shutter mechanism**, dead-weight loaded, (Fig. 5), to verify their cutting action. Their design (Fig. 3 e) is derived from that of the drill bit, reaping thereby the benefit of its good performance. Tests were conducted on graphite and on a specially prepared porous concrete ("Gasbeton") in order to define the correct valve geometry and the most efficient position for the PCD cutters. After final definition of the valves, tests were successfully performed on tuff at ambient temperature, then at -180 C on ice and on the same concrete.

Low Thermal-Vacuum Rig and Corer Tests

An **"external" test rig** (cf. Figs. 6 to 8) has been built to allow testing with full **control of rotation and drill advance** parameters under ambient pressure and, with **external actuation**, under **thermal vacuum (TV)** conditions : it features the main rotational and translational joints of the SAS (items 10 and 12 of Fig.2).

TV tests are performed on this external test rig with the additional implementation of a long **feed-through** between the external actuation and the corer tool inside the TV chamber : as no emphasis on motors is given at this stage of the development programme, the external actuation of the tools was acceptable. The feed-through is made of **two concentric tubes** of ca. 3 m long.: the **outer tube** transmits the torque to the corer rod alone, and the **inner tube** translates the core canister. This concentric feed-through slides on a fixed support mounted on the upper flange of the TV chamber, some 3 m from the sample upper surface, which imposes such a tube length.

At full stroke, some 4 m of tube and corer extend inside the chamber : the lateral stiffness must still be high enough to rotate the corer up to 150 rpm below the first critical speed; it imposes a rigid guidance on the flange. Consequentely, a very careful alignment of the whole driving shaft is necessary, to limit the additional friction on the flange bearings, despite the implementation of an external compliance joint. Tubes are initially subject to a large temperature gradient from outer ambient to that of the cold shroud, and then encounter rapid temperature variations during their downwards displacement while coring.

The concentric joints and the flange bearings present a design challenge, as they need to be vacuum-tight but also to allow rotation and translation of 1 m with a minimum friction, in order not to overload the external actuators, and to limit force-torque variations which pose a control problem.

A hydraulic piston assists the linear actuation during the TV tests, compensating for the additional forces due to the feed-through weight and to the vacuum.

All of these various mechanical, structural and thermal development problems were eventually overcome. For a leak rate allowing to maintain a vacuum of 10^{-3} Pa, the resulting friction torque of the outer seal did not exceed 100 Nm, and was less than 60 Nm for most of the 1 m stroke. Future improvement should reduce this friction still further.

Preliminary coring tests have been repeated with this equipment under low thermal vacuum conditions, in a LN_2 cooled CAM sample (Fig.10) and in porous ice, with equal success as at ambient pressure. Controlling the speed of advance, two 1 m cores were drilled at the lower speed of 30 rpm within 15 min. The observed chips were fine, and there was no clogging problem : no qualitative difference due to the vacuum could be noted compared with previous tests.

Measurements, derived externally from motor current, and thus subject to uncertainties on the additional feed-through friction, indicated that the coring torque did not exceed 10 Nm, well in the order of magnitude of previous values of 4 to 5 Nm. For the next TV tests, adequate force and torque sensors will be placed in the chamber, mounted at the tip of the feed-through outer tube close to the corer rod, in order to measure and control these parameters more directly and more accurately.

Test results achieved so far are promising with respect to the next tests in this programme : in a near future, a prototype **integrated corer** including its **shutter valves** and **shutter mechanism** will also be operated in thermal vacuum.

To our knowledge, this was the first time such a corer's capabilities had been demonstrated in a hard material under extremely cold conditions, using such a low specific thrust and power, and moreover in vacuum.

CONCLUSION

The Sample Acquisition System has been developed to meet the particular and highly unusual requirements of the ROSETTA CNSR mission. A functional design via which well-defined actions are performed sequentially by specific tools has been selected to provide reliability of operation.

A step-by-step test programme has demonstrated so far that a corer and shutter valves with synthetic diamond cutters provide adequate performance under low specific thrust and power at low temperature and in vacuum even for a rocky material with hardness superior to that anticipated in the cometary soil. It is concluded that, subject to there being a successful anchorage, coring is an effective means of cometary soil sampling.

Testing of the prototype corer with bottom shutter and of the surface tool under thermal vacuum will be the next step in the development of the Sample Acquisition System.

The design of the tool described here is expected to find application in the context of other planetary missions in which large soil samples have to be acquired either for in-situ analysis or for return to Earth.

ACKNOWLEDGEMENTS

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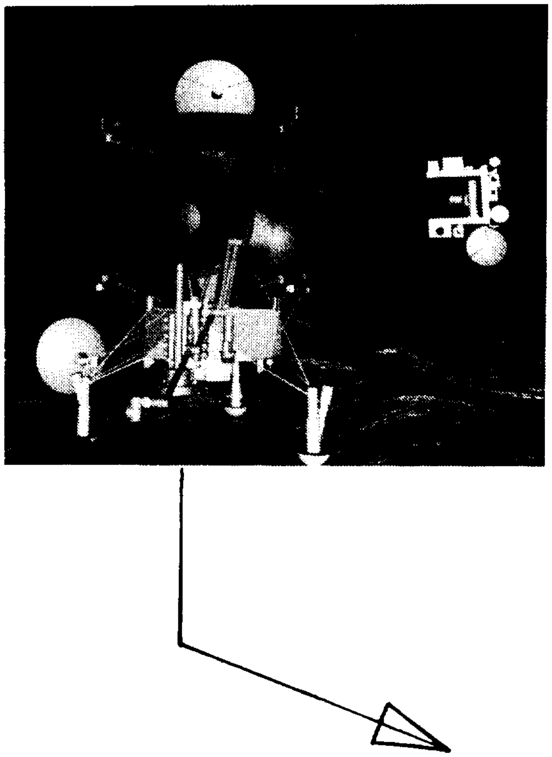
Table 1: Main drill bit test results achieved at -180 C (multistep drill bit, OD 150 / ID 100 mm)

Sample Material		CAM	CAM	CAM	Ice	Tuff
Sample Temperature	C	-190	-190	-190	-170	-180
Depth	mm	380	417	420	501	490
Tool Average Penetration Rate	mm/min	380	296	134	30	1.6
Tool Thrust	N	50	50	20	60-100	60-350
Tool Torque	N.m	4	5	1.5	5-10	3-26
Tool Speed	rpm	150	100	100	150	130-150
Tool Average Power	W	63	52	17	80	100-400
Average Specific Energy	MPa	1	1	1	40	1250



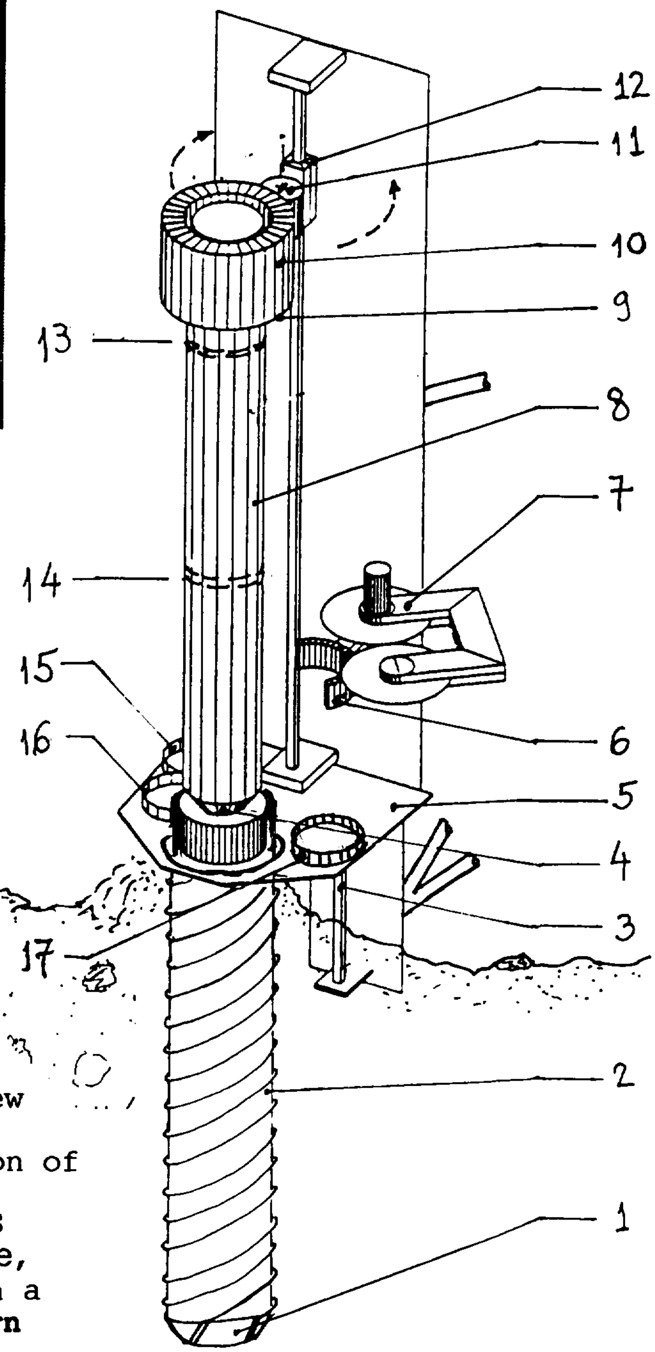


Fig. 1. Sample Acquisition Systems (SAS) overview

top left : artist's conception of the anchored ROSETTA CNSR spacecraft (ref. 7), with **SAS** (early concept) at bottom centre, **manipulator arm** sampling with a **surface tool**, and **earth return capsule** at the centre.

right : present SAS design, sketched after extraction of the 1 m core sample. **Main elements** : 1 : drill bit; 2 : torque tube; 3 : secondary linear joint; 4 : shutter valves; 5 : support table; 6 : gripper; 7 : external cutting device; 8: core canister; 9 : separable link; 10 : main rotary joint; 11 : ancillary rotary joint; 12 : main linear joint; 13, 14 : resp. upper and middle positions to be cut; 15-17 : caps.

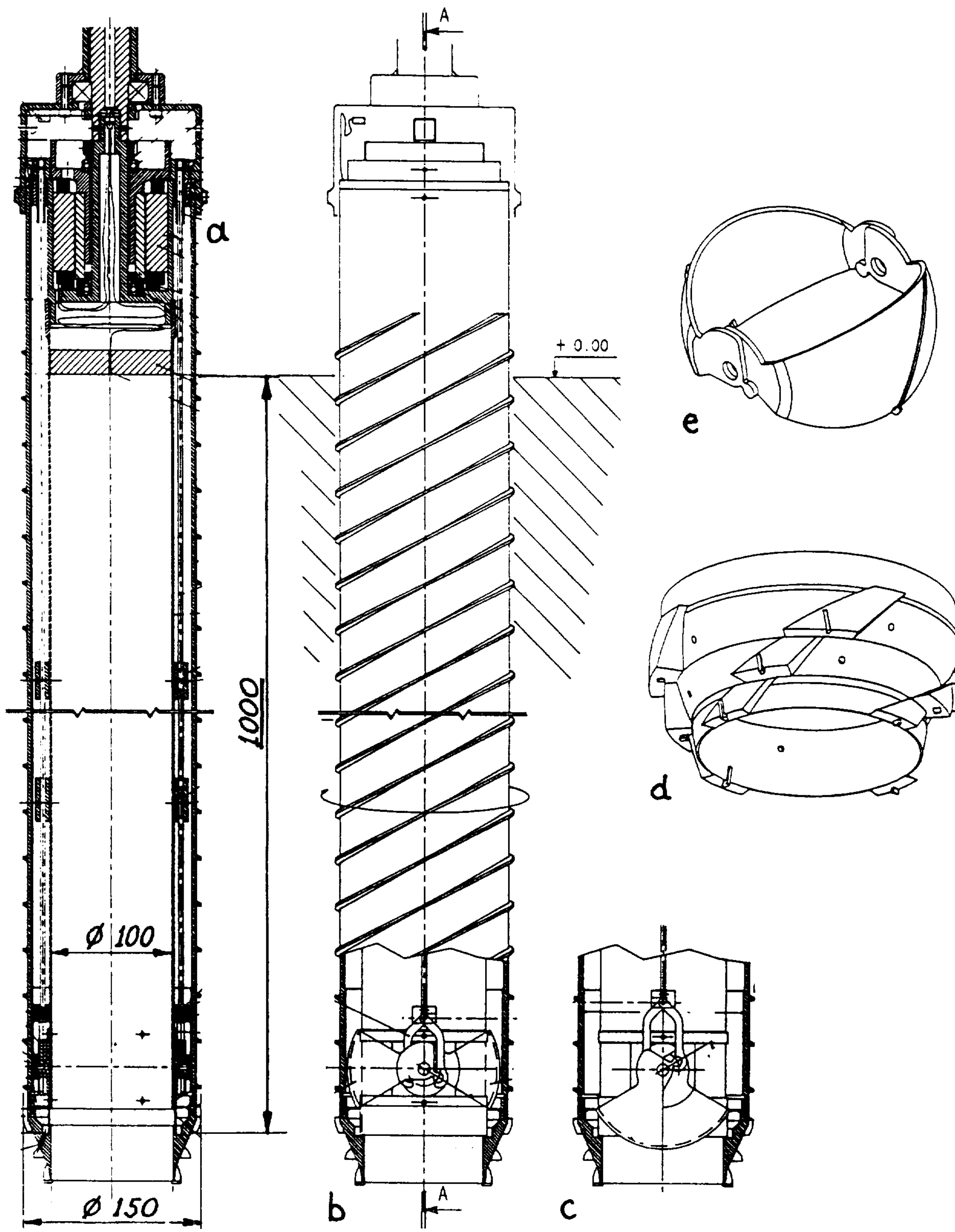
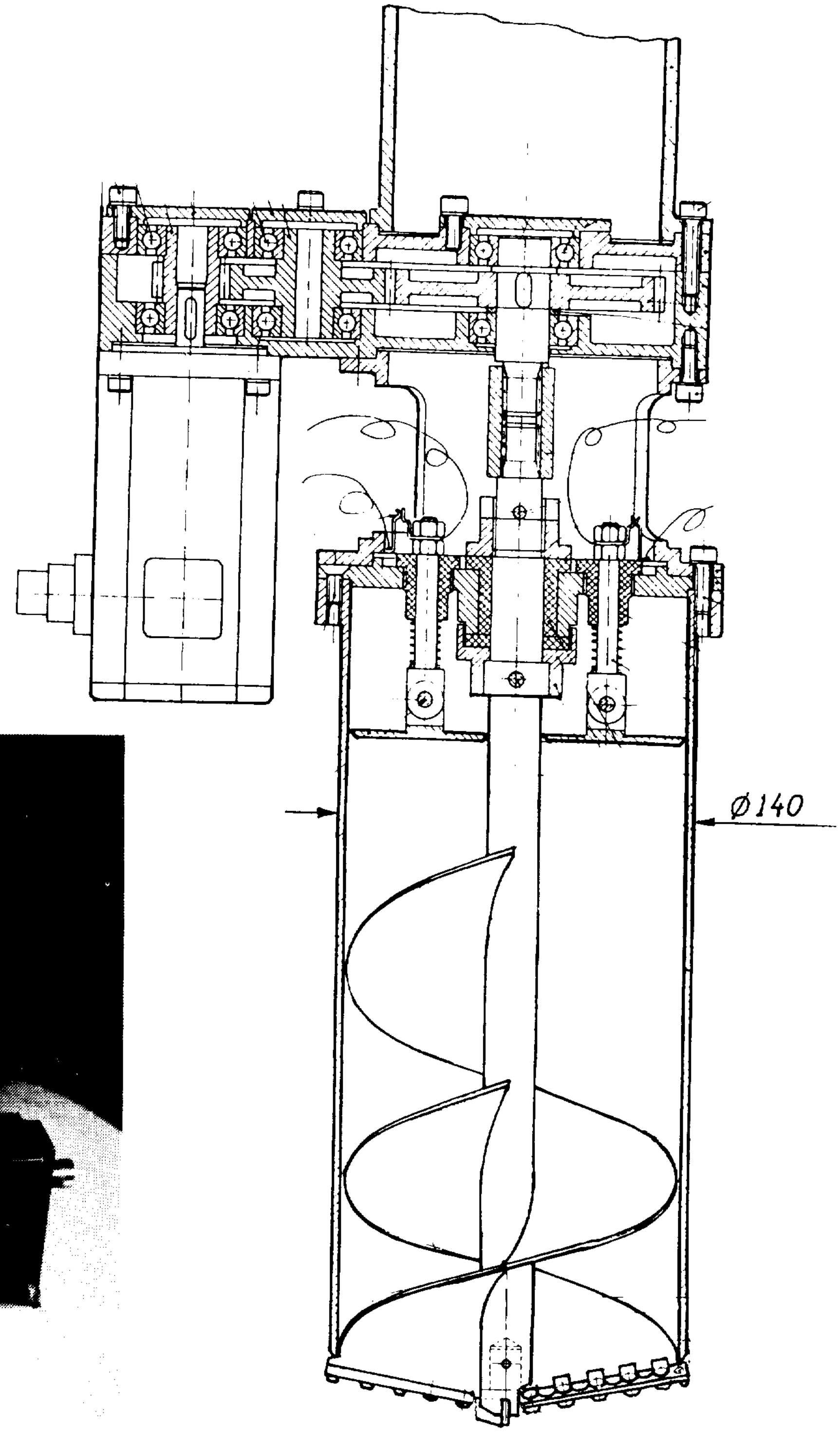


Fig. 2. Integrated corer tool prototype.
a : shutter mechanism; b, c : shutter linkage;
d : multistep drill bit; e : shutter valves.



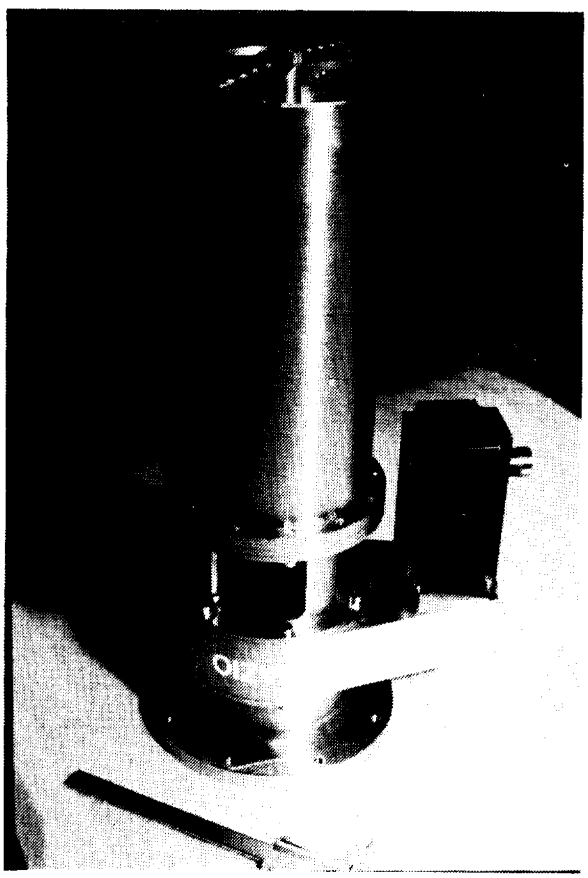


Fig. 3. Surface tool prototype

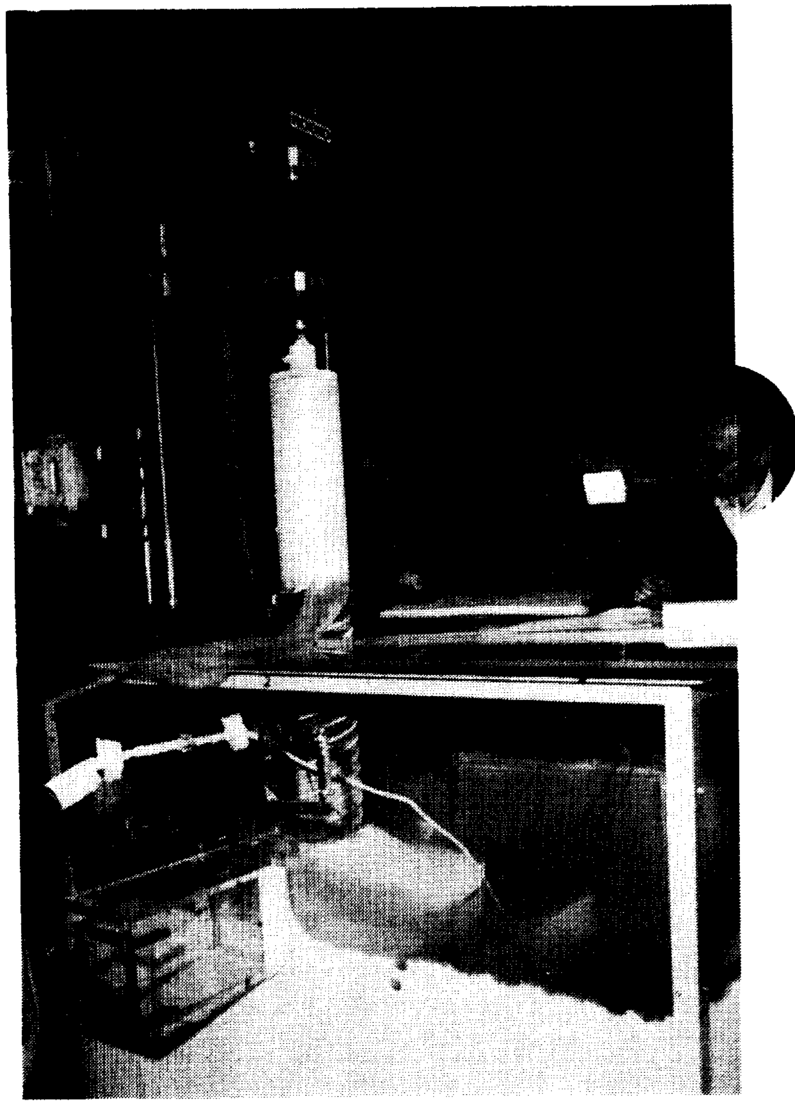


Fig. 4. Early test rig during low temperature coring under nitrogen atmosphere

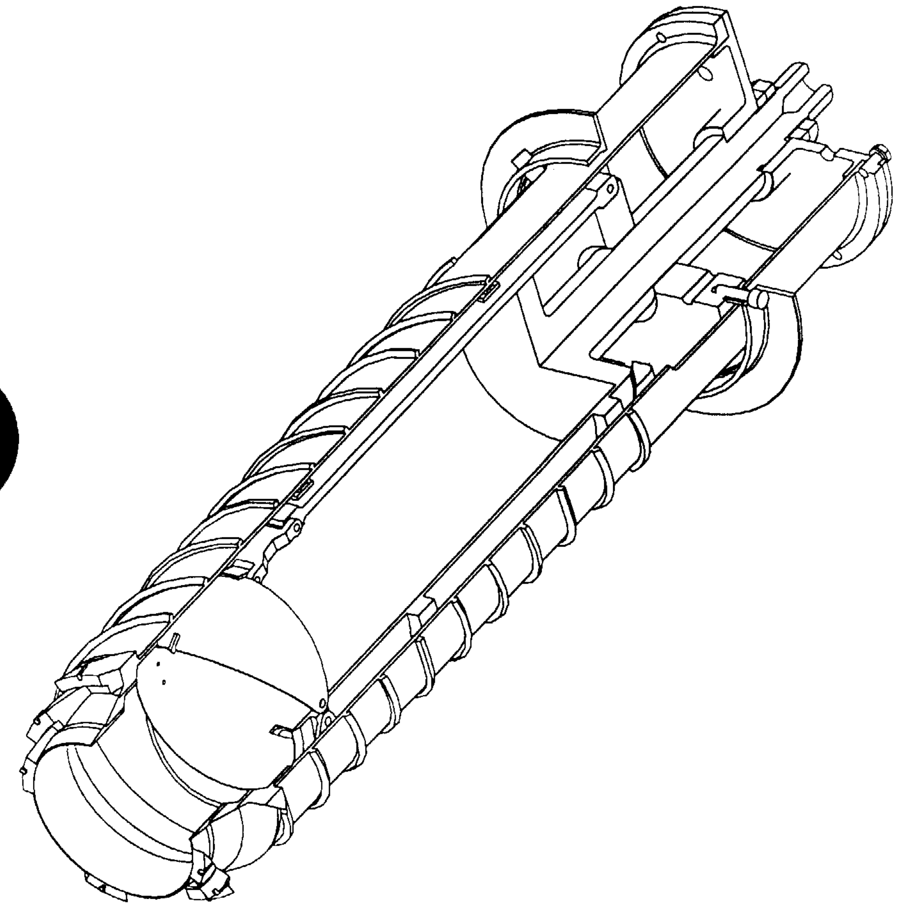
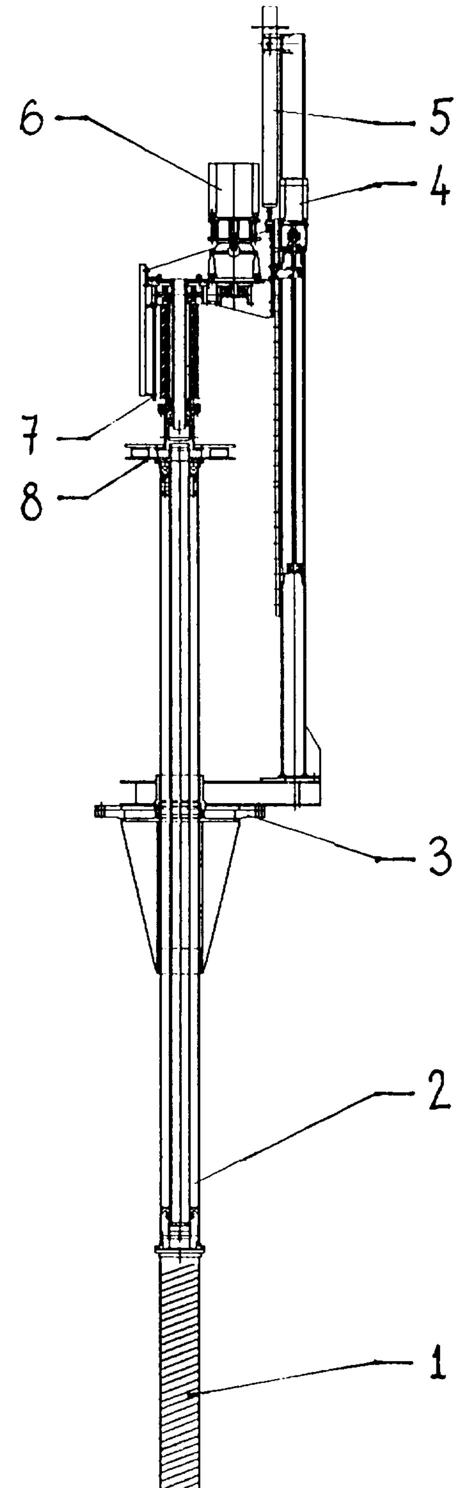


Fig. 5. Shutter valves development model



1 : corer tool
2 : feed-through
3 : interface with TV chamber
4 : linear actuation
5 : hydraulic piston
6 : rotary actuation
7 : sliding contacts
8 : compliance joint

Fig. 6. External test rig, main components for Low TV tests

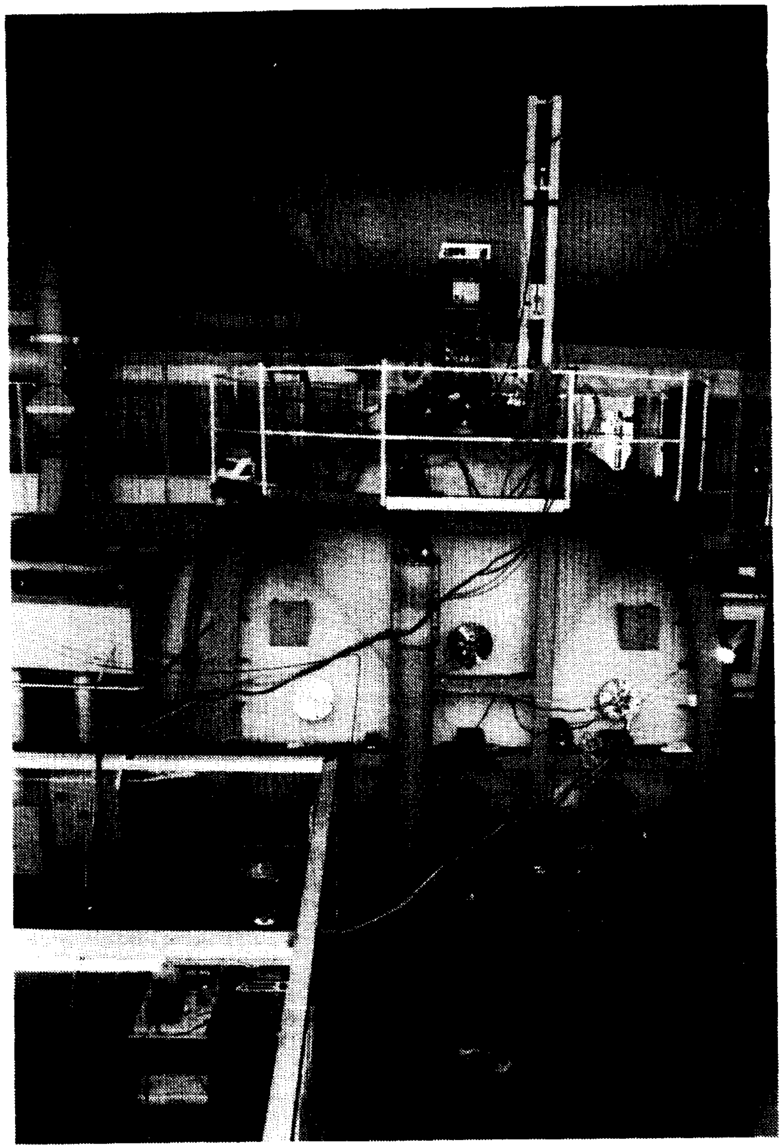


Fig. 7. External test rig on TV chamber

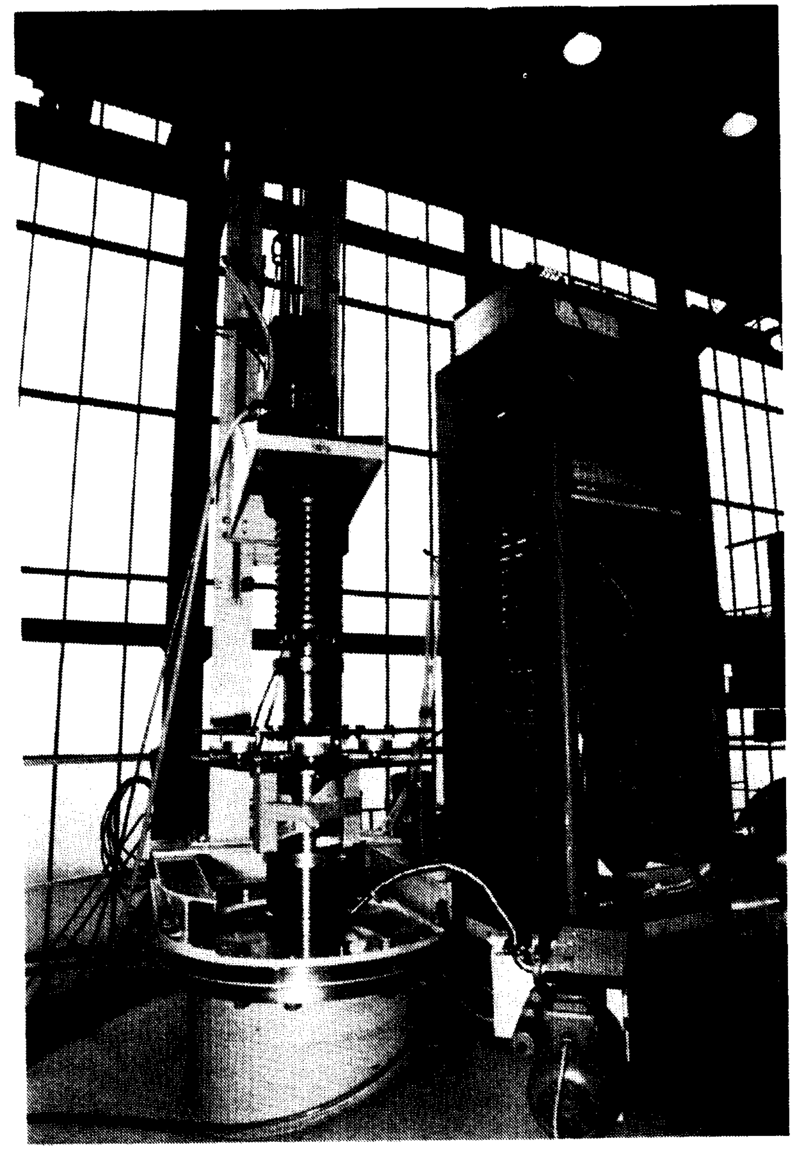


Fig. 8. External test rig and controls

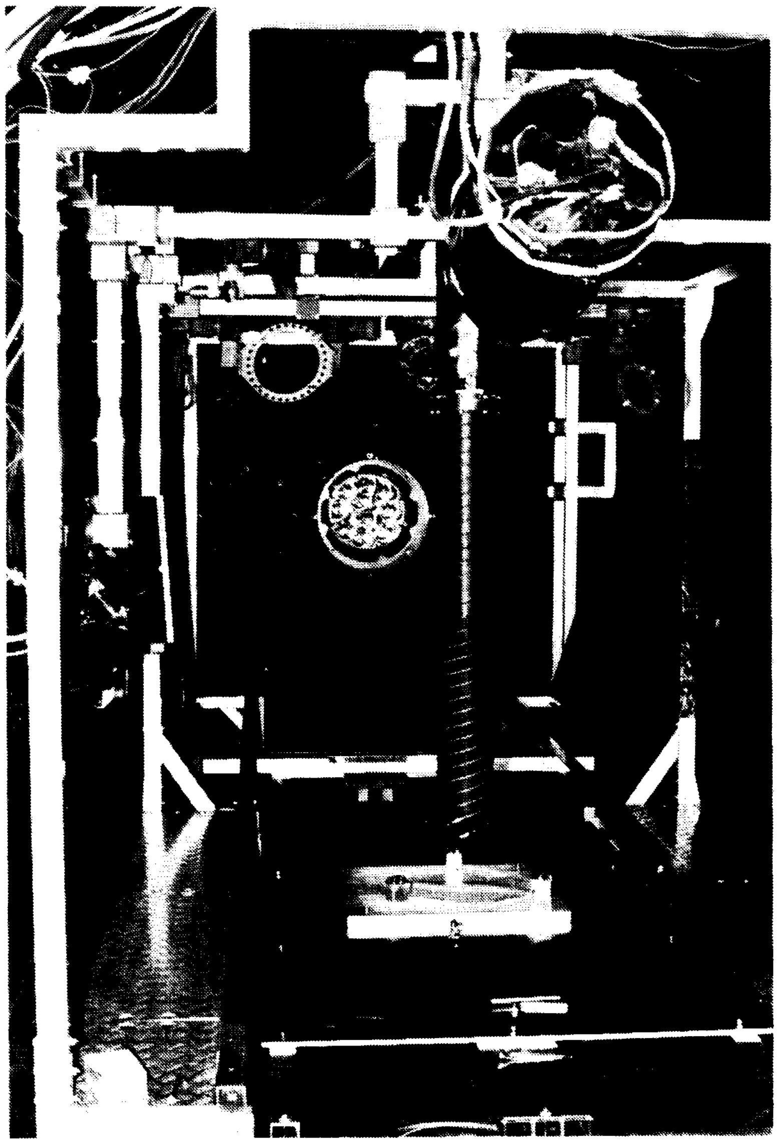


Fig. 9. Corer tool prior to TV tests

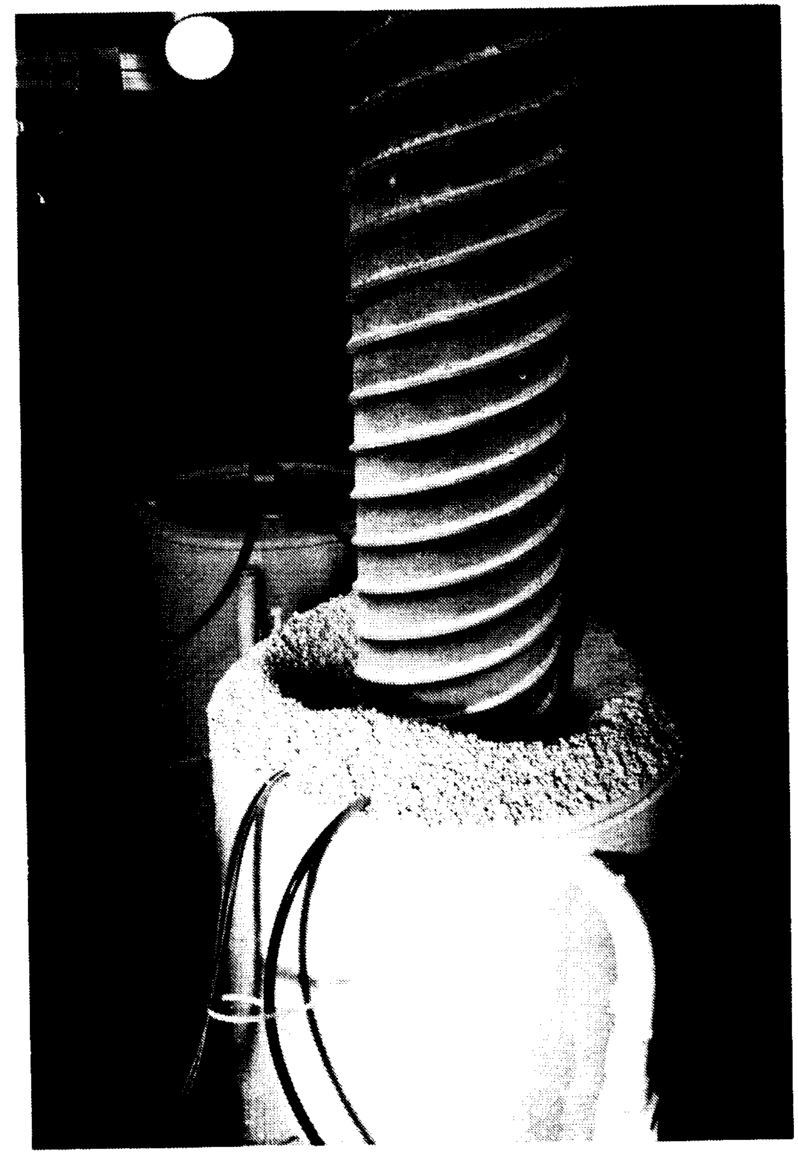


Fig. 10. Corer with cometary analogue sample

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