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SMA APPLICATIONS IN AN INNOVATIVE MULTISHOT DEPLOYMENT MECHANISM

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ABSTRACT

This paper deals with an innovative Deployment and Retraction hinge Mechanism (DARM), developed by CONTRAVES ITALIANA in the frame of a technological program which has been funded by Italian Space Agency (A.S.I.). The mechanism includes two restraint/release devices, which enable it to be stable in its stowed or deployed position while sustaining all associated loads, and to carry its payload by remote command.

The main characteristics of the DARM are as follows:

- deployment and retraction movements are spring actuated
- the available amount of functional sequences is almost unlimited
- no use of electrical motors is made.

These features were accomplished by:

- the application of a special kinematic scheme to the mechanical connection between the spring motor and the swivel head arm;
- the use of Shape Memory Alloys (SMA) actuators for both release and spring recharge functions.

DARM is thus a mechanism which can find many applications in the general space scenario of in-orbit maintenance and servicing. In such a frame, the DARM typical concept, which has a design close to very simple one-shot deployment mechanisms, has a good chance to replace existing analog "machines."

Potential items that could be "moved" by DARM are:

- booms for satellite instruments
- antenna reflector tips
- entire antenna reflectors
- solar panels.

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INTRODUCTION

The DARM concept was established at the end of a "general purpose" Phase "A" of the ASI/CONTRAVES Italiana program. The objective of the program was to define and develop an innovative space mechanism which could have concrete applications in both the actual and future space scenario. After the general feasibility "A" phase, a Predevelopment B1 phase started where the main objective was mechanism functional concept validation. A functional model was built and successfully tested. At the end of this phase it was demonstrated that:

- a spring-actuated hinge deployment mechanism could also perform retraction movements without any configuration change, and that the high accuracy of both movements and final positions could be achieved;
- that two complete operative sequences (each including one deployment and one retraction) could be accomplished and guaranteed;
- two open points did still exist and had to be solved in the development phase in order to make the mechanism a real autonomous and high performance device:
  - to remotely actuate release of mechanisms movements
  - to increase the available amount of functional sequences.

Thus, the subsequent B2 phase – the real development one – was initiated with the final objective of closing such open points and completing design activities, up to manufacturing and testing of an Engineering Model. To this aim, a specific application of the mechanism was found, and the associated technical specifications were taken into account: the Engineering Model was designed as the Antenna Deployment Mechanism of T.L.C. antenna reflectors of ITALSAT 2 satellite.

As far as DARM peculiarities are concerned, the following can be said.

- The spiral spring motor turns a crank by applying a torque at its spin axis. The crank is connected by a sliding surface coupling to a gliph element, and causes the element to oscillate within a specific angular range. The swivel arm is coupled by a gear to the gliph. The arm's stowed and deployed positions correspond to the angular positions where the gliph inverts its angular speed. At that point, the latches of the restraint/release devices lock the arm.
- SMA actuators allow remote actuation of two important functions of the mechanism:
  - releasing of the swivel arm to let it pass from stowed to deployed position and vice versa by direct action on the latches;
  - recharging of the spiral spring motor during non-active periods, such as after any deployment when the mechanism is not required to move.

For both the above cases, SMAs were used in the design of linear actuators. These actuators are equipped with local heaters in order to perform their functions. The use of SMAs was decided as an alternative to other traditional electrical actuators after a trade-off study, and the final choice was justified by consistent mass, reliability, and low complexity advantages. SMAs are conveniently used in a wide range of civil and industrial applications (thermal valves, heat sensitive links, wire detection systems, control systems, connectors, etc.), but recently, European and non-European symposia on the subject of mechanisms have demonstrated the increasing interest also of the Space Community for such innovative and versatile materials.

A short technical description of the DARM Engineering Model, with special emphasis on SMA actuators, and a synthesis of development tests is presented, where the features of those innovative elements are well highlighted.

TECHNICAL DESCRIPTION

The DARM Engineering Model is shown in Fig. 1. Its assembly drawings, as well as its main subdevices, are shown in Fig. 2.

The mechanism is constituted by:

- a Main Structure (M.S.) (see Fig. 3), which includes external mechanical interfaces to the satellite support wall, and which supports all other elements;
- a Swivel Head Arm (S.H.A.), which includes external mechanical interfaces to the payload (antenna reflector arm) and is pivoted to the M.S.;
- Functional Elements.

DARM can be considered as a modular mechanism, where the main functions are accomplished by means of physically separable elements, or elements groups, even though the Engineering Model has a particular compact integrated configuration.

The principal modules are:

- Hinge Trunnions (M.S. and S.H.A.)
- Spring Motor (for deployment and retraction) (S.M.)
- Motion Inversion Device (including gliph and crank) (M.I.D.)
- Spiral Spring Recharge Device (S.S.R.D.)
- Two Restraint/Release Devices (R./R.D.)

The first four modules constitute the mechanism Main Body, while the two R./R.D.s perform an independent function and would be capable of doing so even if they were mounted far from the Main Body itself. For instance, the Main Structure could be "split" in three parts with minor design changes (see dotted lines in Fig. 2), and the R./R.D.s could be accommodated according to a different layout (the Probe Section of these should be mounted on the payload structure in this case).

Spring Motor and Motion Inversion Device

Only a few words will be said about this traditional part of the mechanism.

Energy for both deployment and retraction movements is stored in a preloaded (Teflon coated) spiral spring. The spring torque is transmitted to the S.H.A. by means of a kinematic chain, which is capable of inverting the arm rotational movement every 90 degrees. The kinematic chain is inspired by a classical mechanical system: the Fairbairn's Guide. The minor changes which were introduced in such a basic system are described in Fig. 4.

The S.M. and M.I.D. are supported by a separate lightweight structure which is fixed sideways to the M.S. Minor changes to this separate structure enable the S.M. and the arm hinge axis to be directly connected. In this case, the M.I.D. cannot be integrated, and the mechanism would become a "one shot" machine.

Spiral Spring Recharge Device

Figure 5 shows in detail all the parts that constitute the device. The S.S.R.D. is the device that eliminates almost entirely the problem of the limited number of maneuvers of DARM by recharging the spiral spring during idle times. By taking advantage of the SMA's characteristics, two linear actuators can be created which allow both the translation along its own axis and the rotation of a front-toothed wheel. The synchronization and composition of the two movements can be exploited to produce the rotation of the wheel driven by the front-toothed wheel. This wheel, which is connected mechanically with the spiral spring, can therefore cause the spring to recharge partially. The S.S.R.D. can guarantee a recharge movement of 80 degrees per cycle. Since, in the case of the DARM, the spiral spring has a preloading of 1400 degrees, i.e., about four complete rotations on the axle, obviously it will be necessary to put the S.S.R.D. into motion several times in order to achieve complete recharge. The spiral spring does not have to be completely unwound in order to be recharged. In fact, it can be recharged in any position between 0 (zero) and 1400 degrees, and in this way, the consecutive sequence of the number of cycles to be carried out with the recharge mechanisms can be reduced. The elements created from the SMA operate by means of heating, obtained by electrical resistances in contact by conduction with the elements.

This device was conceived as an option, to a certain extent. The DARM technical requirements included a minimum capability of two deployments and two retractions as the functional performance. The DARM S.S.R.D. can be thus considered as a Functional Model (not yet optimized) to be used for concept validation aims (which were successfully achieved). For this reason, such a device was not included in the mechanism test configuration during environmental tests.

Restraint / Release Devices

The two R./R.D.s perform the following functions:

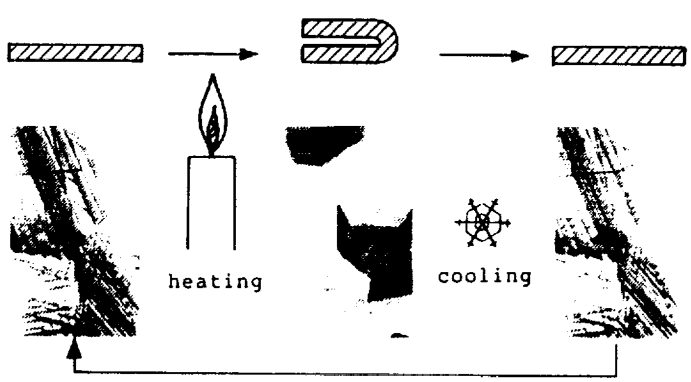
- carry end stops for deployment and retraction of the Arm and/or the associated payload
- carry latches to restrain the Arm and/or the associated payload during launch and in orbit
- sustain launch and operative loads
- release the Arm, allowing it to deploy or to retract

Each R./R.D. includes two fixed subdevices, which can be fully integrated in the M.S., or separately mounted. Two "travelling" subdevices, which carry the probes and must engage in the fixed subdevices at the end of deployment or retraction, can be fixed to the Arm or to an appropriate region of payload structure. Each fixed subdevice includes a reusable release actuator. Several kinds of such actuators are known, and most of them are based on electric motors or magnetic devices. These known actuators have several drawbacks especially related to their excessive mass and size, which are very important parameters in space applications. The known actuators have also shown poor performance when a relatively high force is required to actuate the R./R.D. The S.M.A.-based DARM release actuator overcomes these problems, with its lightweight and small size characteristics and its good performance over repeated operations.

A complete R./R.D. is shown in Fig. 6. With reference to the figure, the operation of the actuator is described. When desired, the power source powers the resistance member (12), which heats the metal strip (10). When the metal strip reaches a selected temperature, it bends, as schematically shown by dashed lines in the drawing, and the pusher member (13) pushes the cam member (7) rotating the lever (5). The ledge (8) is thus disengaged from the hook (4), and the latch moves to the release position, allowing the moving arm to rotate to deploy the structure. When the metal strip (10) cools off, and the electrical resistance is not being powered anymore, the strip returns to the substantially straight position. The strip (10) can repeat this operation several times without any degradation of its physical and geometrical characteristics.

SMA ACTUATORS

The Shape Memory Alloys are able to carry out complicated and versatile motions, achieved only be heating and cooling, without application of any external stress. It is important to know that no lubrication is necessary to obtain an SMA actuator movement, i.e., friction and wear are absent. The shape memory effect has its origin inside the alloy itself. It is caused by a "martensitic" phase transformation occurring at fixed temperatures. Three different characteristics of shape memory behavior are known, whereby the so-called "two way effect" has to be used for actuators. The effect can be represented as in the scheme here below.



Two-Way SMA Effect

The two-way effect is imparted by plastic deformation of the element at low temperature. When subsequently heated above the transformation temperature, the element returns almost completely to its initial shape. All kinds of motion can be achieved: bending or torsion, expansion or contraction. During motion, the element is capable of exerting a force (or torque). Both force and stroke are controlled by the dimensions of the element. The trigger temperature can be adjusted by the manufacturer quite accurately by controlling the percentage of the alloy constituents. The effect can be repeated many times. Two different linear SMA actuators are present in the DARM: the first one is a strip, and is used in the R./R.D.; the second one is a helical spring and is used in the S.S.R.D.

TESTS AND RESULTS

The test plan to which the DARM Engineering Model was submitted included both functional/performance and environmental tests. Besides the above tests, an additional set of tests was specifically addressed to investigate the SMA actuator behavior. In particular, it was decided to submit the release actuator (SMA strip) to the following tests:

- life cycle test,
- functionality at extremely low temperature tests,
- limit performance test.

Test on the Mechanism

All test results are presented below, in the same sequence in which they were carried out.

MOTOR SPRING TORQUE

- MAXIMUM WINDING ANGLE : 1548^0
- SPRING TORQUE : 0.48 Nm
- SPRING STIFFNESS : K = 0 0177 Nm / rad

TORQUE MARGIN (T.M.)

- 1st PHASE– MINIMUM T.M. : + 280%
- 2nd PHASE– MINIMUM T.M. : + 80%
- 3rd PHASE– MINIMUM T.M. : + 205%
- 4th PHASE– MINIMUM T.M. : + 35%

KINEMATIC PARAMETERS

	DEPLOYMENT/ RETRACTION DURATION TIME	MAXIMUM ANGULAR SPEED	MAX MOMENTUM	FINAL SPEED
1st PHASE	11 s	0.25 rad / s	5.5 Nms	0.14 rad / s
2nd PHASE	19.5 s	0.11 rad / s	2.42 Nms	0.05 rad / s
3rd PHASE	12.5 s	0.20 rad / s	4.4 Nms	0.13 rad / s
4th PHASE	25 s	0.08 rad / s	1.76 Nms	0.04 rad / s

MOMENT OF INERTIA I = 22Kg m^2

ACCURACY AND REPEATIBILITY OF DEPLOYMENT ANGLE

	REQUIREMENT	MEASURED VALUES	
		1st DEPLOYMENT	2nd DEPLOYMENT
ACCURACY	≤ ± 54"	+7.95"	+12.4"
REPEATABILITY	≤ ± 36"	−16.45"	−17.4"

FUNCTIONAL TESTS IN VARIOUS THERMAL/PRESSURE CONDITIONS

ENVIRONM. CONDITIONS	POWER SUPPLY	CURRENT ("MINCO" HEATERS)	CONSUMED POWER	ACTUATION TIMES	CONSUMED ENERGY
$T = +20^{o}c$ $P \simeq 1$ bar	30V	1.8A	54W	20 s	1080 J
$T = +50^{o}c$ $P \simeq 1$ bar	30V	1.8A	54W	17 s	918 J
$T = +50^{o}c$ $P \simeq 10^{-8}$bar	30V	1.8A	54W	14 s	756 J
$T = -60^{o}c$ $P \simeq 1$ bar	30V	1.8A	54W	75 s	4050 J
$T = -54^{o}c$ $P \simeq 10^{-8}$bar	30V	1.8A	54W	40 s	2160 J

RANDOM VIBRATIONS

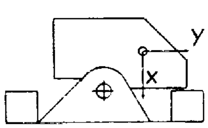
	G RMS
" X " AXIS	22.03
" Y " AXIS	23.4
" Z " AXIS	25.62

DURATION : 2 MINUTES
RESULT : NO DAMAGES AT ALL

STIFFNESS

STIFFNESS :	MEASURED VALUE
RADIAL	$0,26 \times 10^{8}$ N / m
AXIAL	0.19×10^{7} N / m
ON STATION : AGAINST "LATCH"	0.18×10^{6} Nm / rad
ON STATION : AGAINST "STOP"	0.39×10^{6} Nm / rad

LATCH–UP SHOCKS AT INTERFACE (AVERAGE VALUES)



	SHOCK IN "X" DIRECTION (g)	SHOCK IN "Y" DIRECTION (g)
1st PHASE	3.86	3.45
2nd PHASE	1.24	1.38
3rd PHASE	3.29	2.59
4th PHASE	1.03	1.16

STATIC LOADS

1) 1200 N RADIAL
2) 1500 N AXIAL + 1000 N RADIAL (SIMULTANEOUSLY)

RESULTS : NO DAMAGE AT ALL

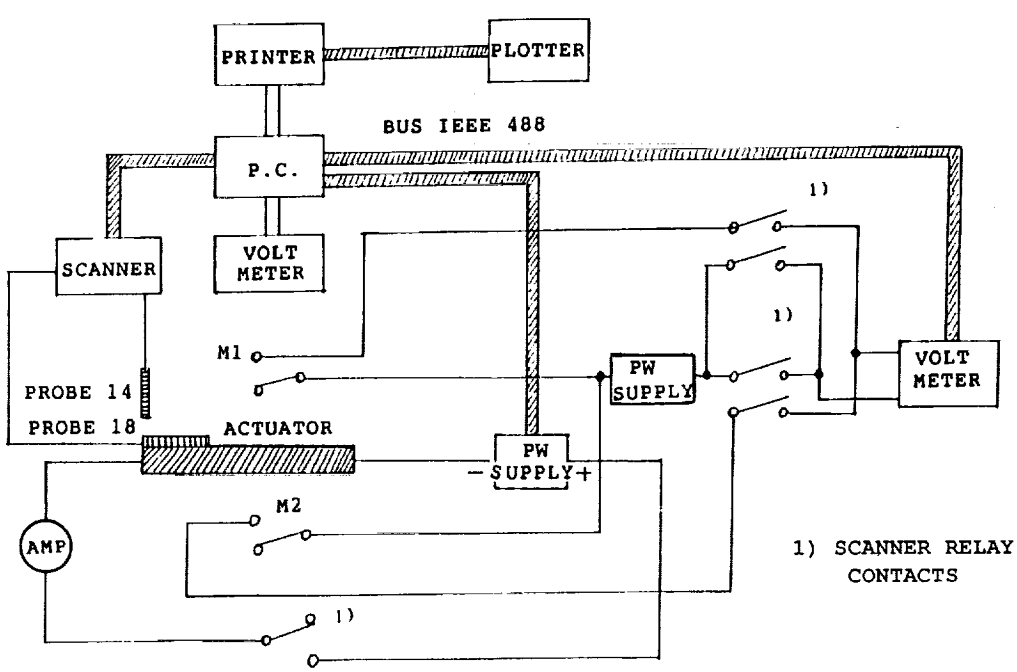
Tests on SMA Actuators

The SMA strip underwent all the functional and environmental tests to which the whole DARM was subjected. After successful completion of such tests, two strips underwent additional tests with the following results.

Life-Cycle Test

- Number of cycles: 400
- Every single cycle had the following sequence:
  1: external temperature stabilization
  2: heating up to stroke completion (indicated by a position sensor)
  3: stop heating
  4: natural cooling down to reverse stroke completion (indicated by position sensor)
- Configuration: actuator without any significant load
- Monitoring and commands:
  - active and reverse stroke associated duration
  - strip external surface temperature (with maximum temperature limitation)
  - ambient temperature.

The test scheme is shown below:



Note: The test setup is shown in Fig. 7, and the test results are shown in Fig. 8.

Low Temperature Test

- Ambient temperature stabilization at -150 C degrees.
- Heating up to active stroke completion (visually checked by means of a millimetric reference).
- Monitoring of the strip external surface temperature.
- Natural cooling down.

The test setup is shown in Fig. 9, and the test result is shown in Fig. 10.

Maximum Load Test

Many functional tests were performed on the test item after completion of the Life Cycle and Low Temperature tests using increasing loads in order to verify the SMA strip function capability and to find its "ultimate load." The test setup is shown in Fig. 11. The test results are summarized in the table here below.

Test Label	Load [N]	Displ. [mm]	T_{amb}. [°C]	Stroke Duration Act.	Rev.	Voltage [V]	Current [A]
1	0	7	20	34	270	24	1.6
2	5	"	"	"	"	"	"
3	10	"	"	"	"	"	"
4	15	"	"	"	"	"	"
5	20	"	"	"	"	"	"
6	25	"	"	"	"	"	"
7	30	"	"	"	"	"	"
8	35	"	"	"	"	"	"
9	40	"	"	"	"	"	"
10	45	"	"	"	"	"	"
11	50	"	"	"	"	"	"
12	55	6.9	"	"	"	"	"
13	60	6.8	21	"	"	"	"

CONCLUSIONS

The DARM Engineering Model has successfully passed a severe test program, which has demonstrated the mechanism concept and functional capability to fulfill a spread set of technical requirements. It can be considered as a reference point in the general scenario where deployment and retraction capabilities are required to a hinge mechanism, and when such a mechanism must have a simple and reliable configuration and must not necessarily require electrical power to perform its main functions.

DARM includes innovative SMA actuators for its release and self-recharge functions. The specific tests which have been performed on such extremely simple actuators have highlighted their high reliability and their capability to perform their function with:

- very good repeatability during their expectable life (i.e., one hundred cycles),
- acceptable performance variations at the end of very long life (four hundred cycles),
- peculiar advantages (with respect to other actuators) at very low temperatures (no friction),
- high adaptability to mechanical overloading (about ten times the nominal load without any permanent damage).

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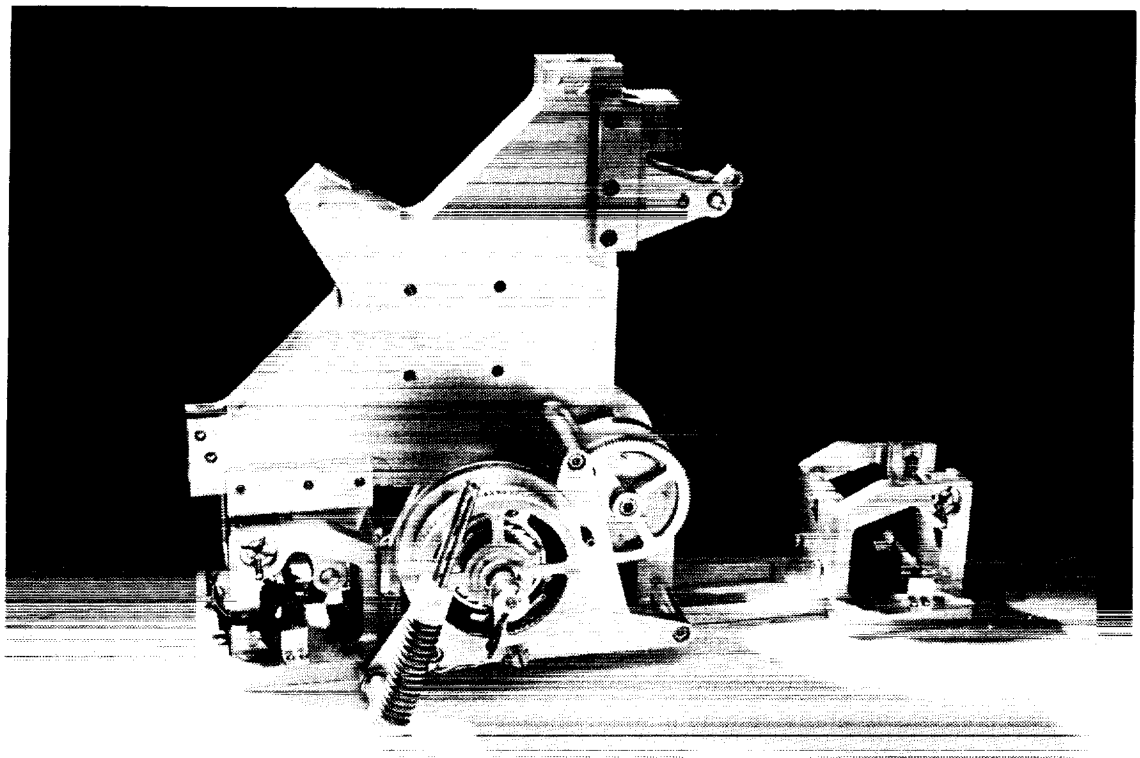

Fig.1 - DARM Engineering Model

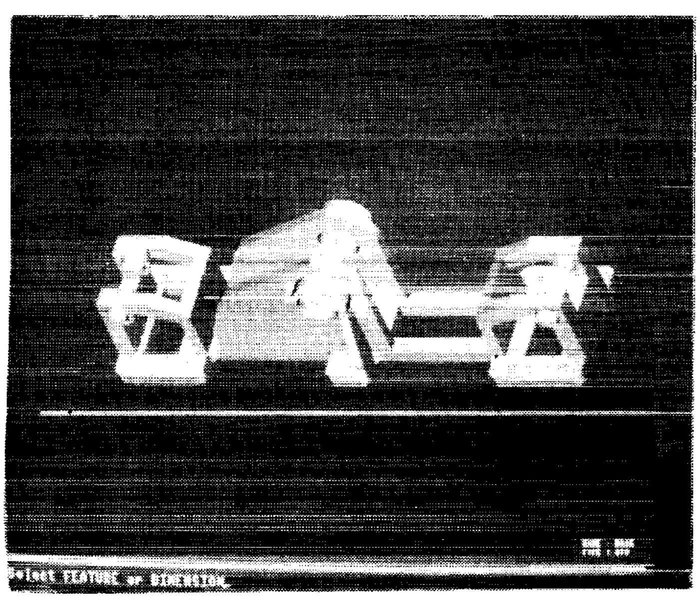

Fig.3

Computer generated image of Main Structure (M.S.)

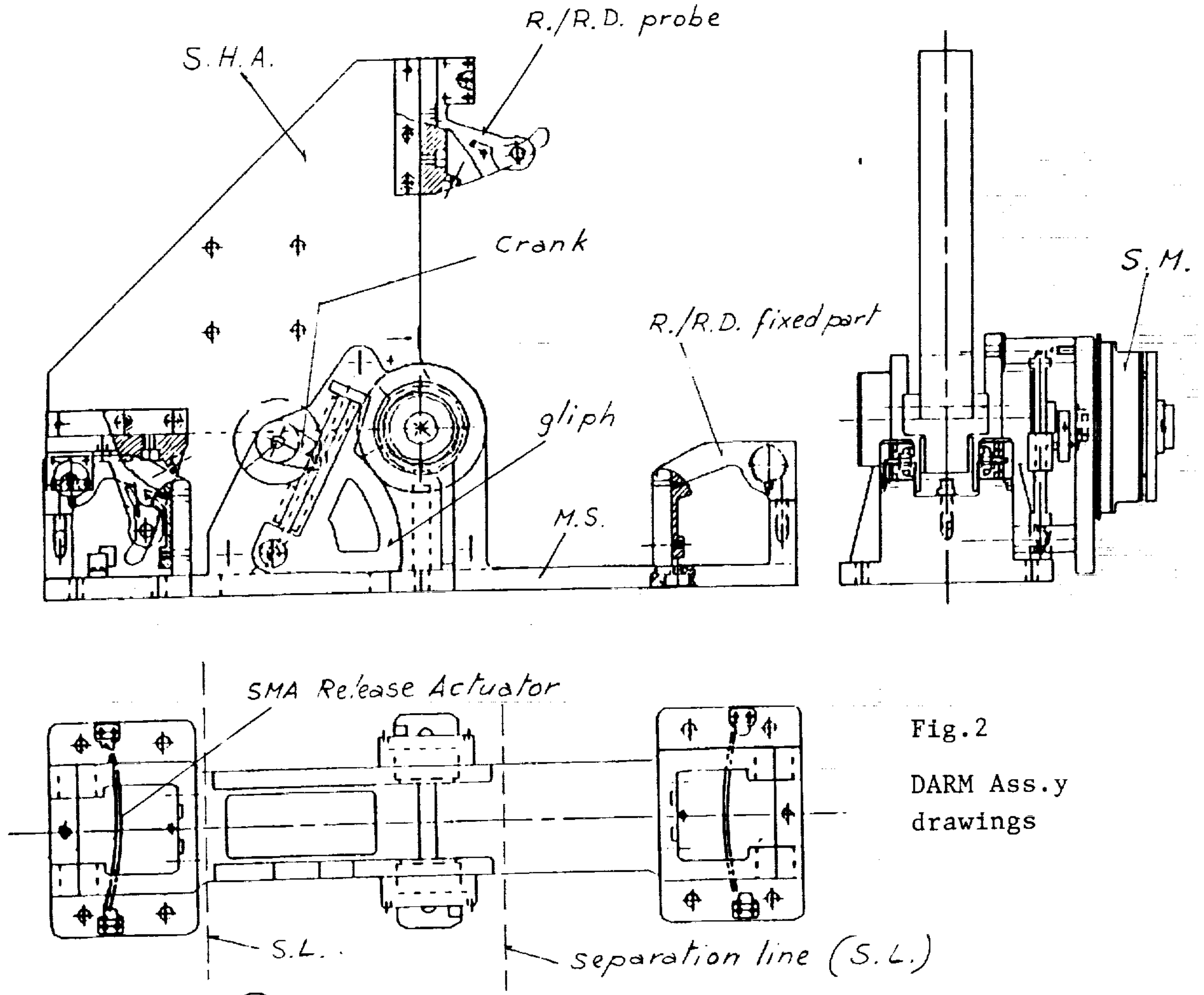

Fig.2

DARM Ass.y drawings

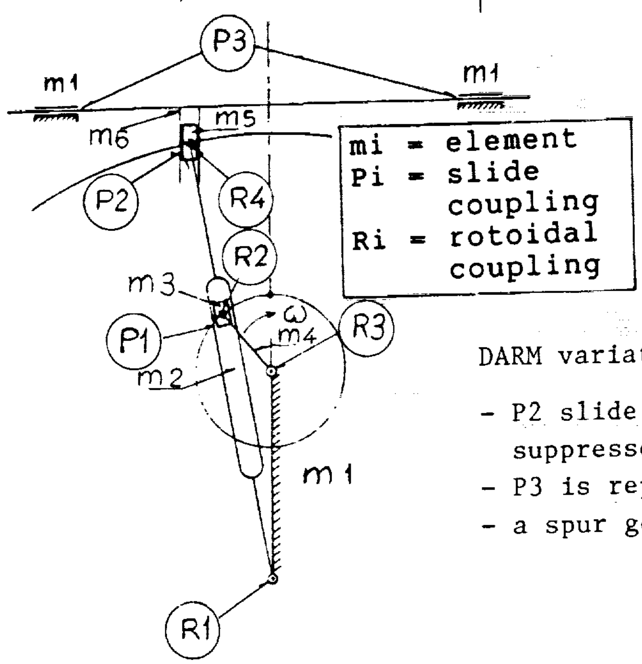

Fig.4

The Fairbairn's Guide

DARM variations:

- P2 slide coupling and m5 element are suppressed
- P3 is replaced by a rot. coupling
- a spur gear coupling connects m6 and m2

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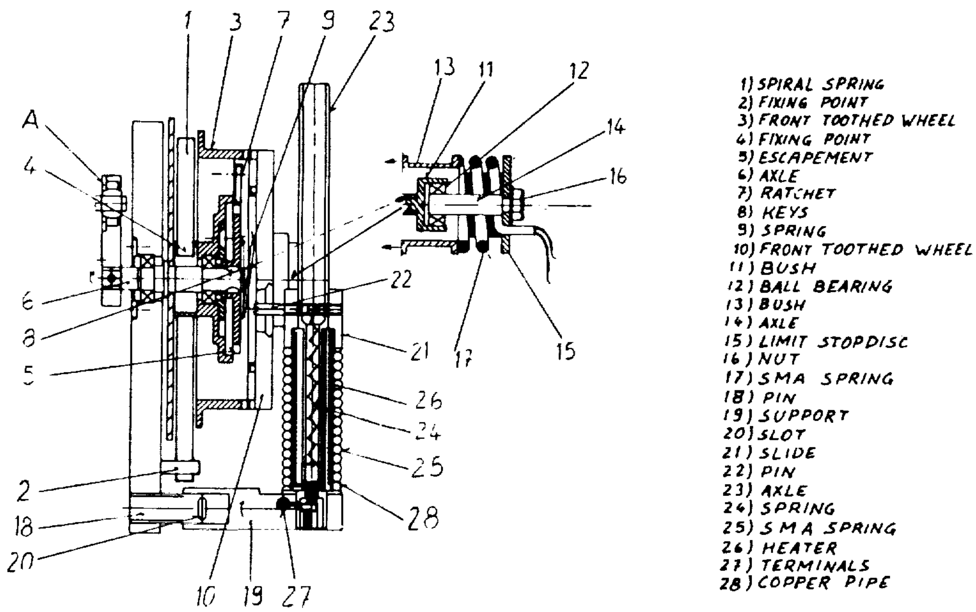

Fig.5
Spiral Spring Recharge Device (S.S.R.D.)

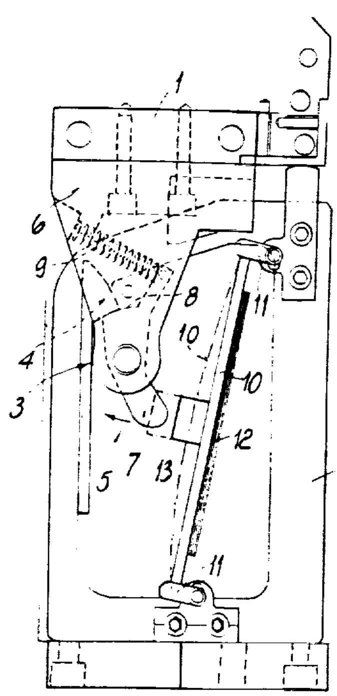

Fig.6
Restraint/Release Device (R./R.D)

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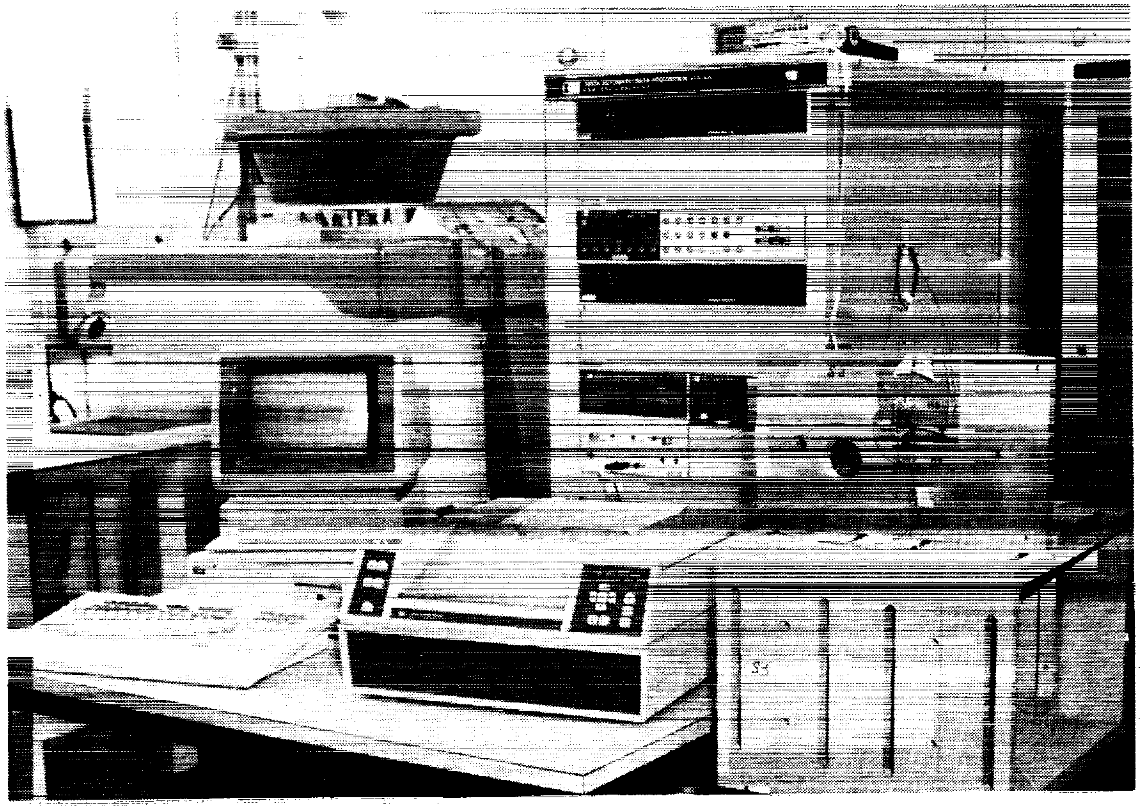

Fig.7 - Life Cycle Test set-up

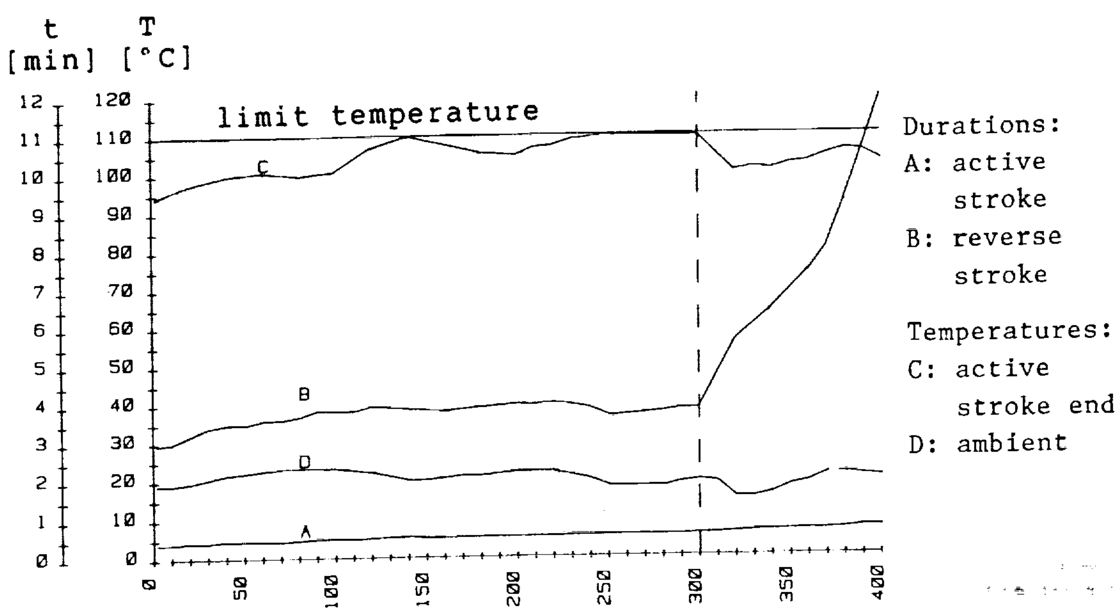

Fig.8 - Life Cycle Test results

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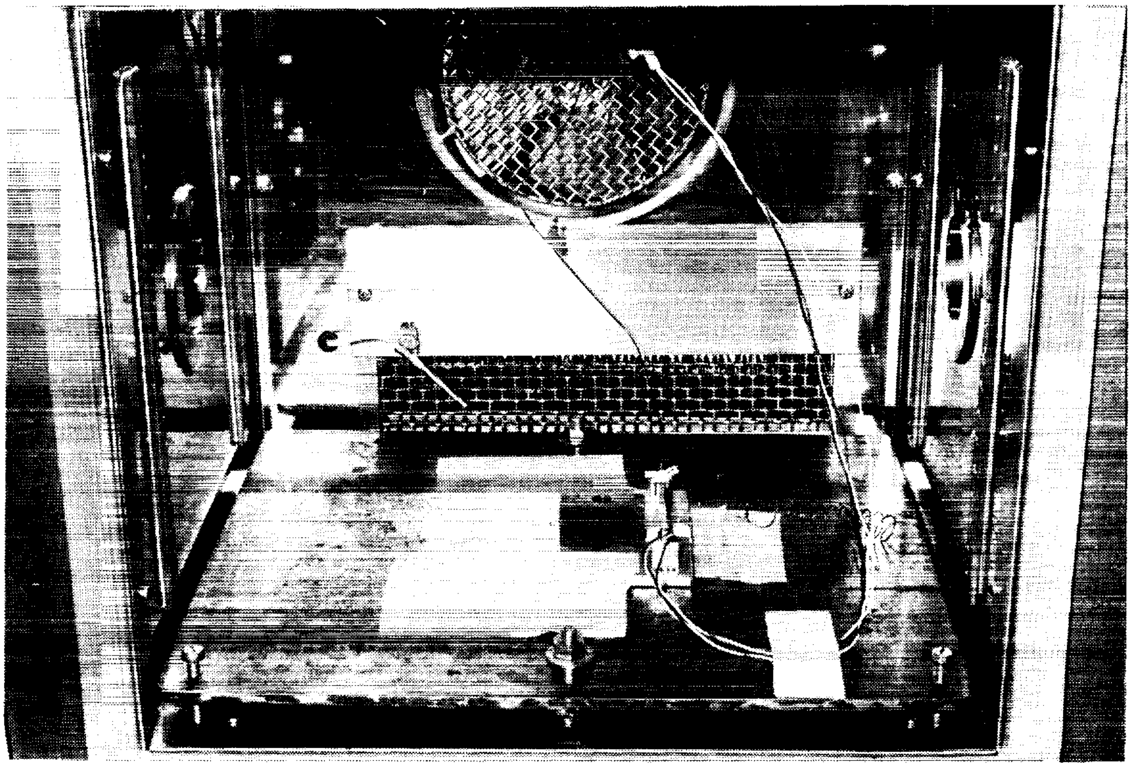

Fig.9 - Low Temperature Test set-up

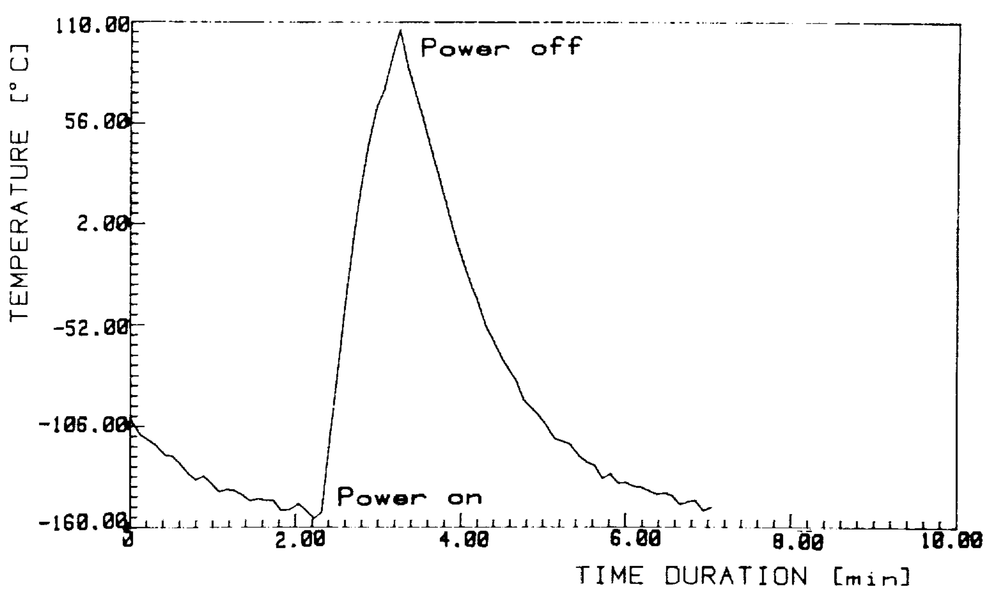

Fig.10
Low Temperature Test results (strip temp.)

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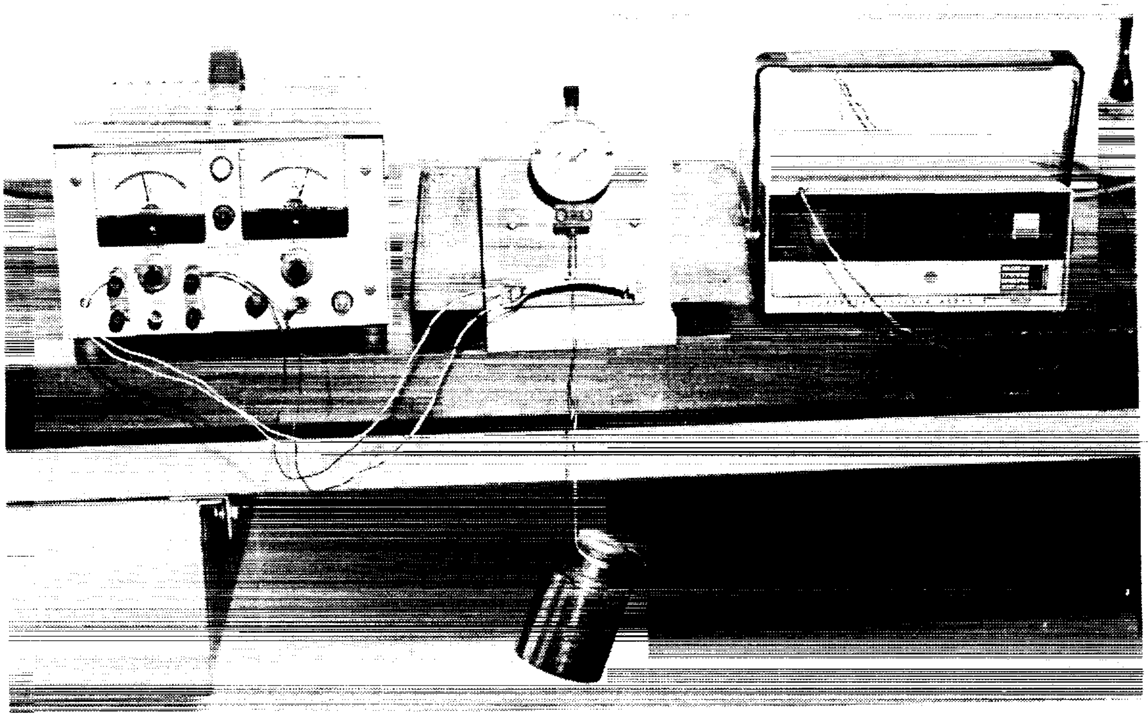

Fig.11 - Maximum Load Test set-up