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Concept of Space Suit Enclosure for Planetary Exploration

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Abstract

At present advanced projects of the early XXI century are beginning to develop. These projects include lunar base development and manned missions to Mars. The space suit is one of the basic requirements for successful implementation of future programs. The space suit enclosure enables mobility of crewmembers wearing pressurized space suits which will be required to complete these missions.

Requirements on Planetary Space Suit (PSS) enclosure design, especially for elements providing mobility of the lower torso assembly will be different from these on orbital space suit enclosure design, intended for zero gravity conditions.

The PSS enclosure provides cosmonaut/astronaut movement on planetary exploration surfaces, ascent/descent of the Landing Module ladder, suited crewmember's bending etc. Thus this PSS component will play a considerable role in successful fulfillment of extra-vehicular activity (EVA) tasks on planetary surfaces.

The paper comprises the following:

- Analysis of the specific environmental conditions and EVA characteristics on the Moon and Mars
- Major PSS enclosure requirements
- PSS enclosure design concepts analysis
- PSS lower torso assembly concept for the Moon and Mars

Introduction

Russia and the USA have accumulated great experience in the development and use of space suits for near-earth orbit EVA and for their lunar programs. This experience can be applied to development of the next-generation space suit for the Moon and Mars. To a great extent, the success of these future projects will depend on selection of a PSS type, PSS enclosure concept, which provides for required cosmonaut mobility and other mission requirements.

As is known, space suit enclosure mobility is provided by joints, which serve to bend enclosure elements, and ball bearings, which serve to rotate enclosure parts relative to each other. On the suit enclosure, various combinations of joints and bearings are possible. If we compare the PSS and orbital EVA space suit operational environments, additional factors, which influence the PSS design are evident; e.g., gravity is a considerable influence on the PSS enclosure including the lower torso assembly joints and bearings. The PSS weight limitation makes us trade off between mass and mobility. Use of many bearings to provide maximum mobility at minimum effort may result in increasing the suit weight and dimensions and complicate suit operations. Compromise versions combining joints and smaller numbers of bearings, are possible.

Hereafter, in analyzing the enclosure concept, the authors take into account the experience obtained in development of both the Lunar space suits (US A7LB and RF "Krechet") and orbital space suits (US EMU and RF "Orlan") as well as test results for the latest development of space suits.

Selecting the PSS enclosure design concept, the authors first of all take into account the provision of such factors as:

- Minimal mass,
- Range of motion, necessary for the planetary exploration,
- Anthropomorphic (natural) suited crewmember movements,
- Ease of space suit donning/doffing.

The main purpose of the PSS is to provide for EVA on the planetary surface. The issues of suit enclosure selection are considered here as applied to this purpose. Other possible considerations, usage for EVAs during interplanetary flight and PSS usage during landing/take-off as an IVA suit have not been addressed. In this connection, the paper pays most attention to suit elements providing for walking mobility i.e. suit lower torso assembly (LTA). The influence of life support system (LSS) characteristics, robotic devices, etc. on suit enclosure design have not been discussed for brevity.

Space suit operations on the Moon and Mars.

Table 1 presents some comparative data on environmental conditions, which must be taken into account in developing and designing the PSS.

Table 1. Comparison of environmental conditions

#	Environmental Condition	Near-earth orbit	Moon	Mars
1	Gravity	0	1.62 m/sec^2 (0.17g)	3.91 m/sec^2 (0.38g)
2	Pressure	0.0 bar	0.0 bar	6...11 bar
3	Surface temperature range	−163...+112°C	−163...+112°C	−143...+17°C

Among the tabulated data for the development of the PSS enclosure design concept, the gravity environment has the greatest impact. Another important factor is exposure to dust on the Moon/Mars surfaces. It goes without saying, the suit outer garment – thermal micrometeoroid garment (TMG) will be required to protect the PSS enclosure from many dangers including dust penetration. Special design features are foreseen on the TMG/PSS enclosure to provide for:

- Cleaning dust from the TMG/PSS enclosure
- Repair or replacement of TMG/PSS enclosure damaged components.

When performing planetary exploration tasks, the suited crewmember must walk on uneven terrain. The PSS design must allow the crewmember to stand up after falling and take intermediate positions (on all fours, kneeling etc.), necessary to take the vertical position. The PSS enclosure must also allow the suited crewmember to take different static postures without excessive effort. Moreover, the subject may need to take these positions to complete a set of activities and exploratory tasks. This suggests a list of static postures at which the PSS joints should be in an equilibrium state (i.e. position maintained with little or no effort):

- Standing up
- Bending forward
- Sitting
- On knee(s)
- On all fours.

In the process of planetary exploration, a cosmonaut/astronaut will be required to retrieve rock samples and the PSS enclosure must accommodate this task. In order to reach the planet surface with a hand and take a sample of soil/rock, the crewmember must bend forward, squat, or kneel. Each of these motions is implemented by interaction of a set of joints/bearings that is a specific feature of the PSS.

The necessity to provide easy walking on the planetary surface is another specific requirement for the PSS. It is well known that flexible-soled footwear makes walking easier. The issue concerning the definition of the degree of flexion of the sole for the PSS boots must be studied.

Performing intensive EVA, comfort provision for the suited crewmember are of great importance. In order to provide comfort for the crewmember wearing the suit, special soft inserts able to prevent pinching, numbing, chafing, cutting, etc. must be included in the PSS enclosure design (thermal comfort requirements are not discussed in this paper).

The Moon/Mars relief is uneven. The LTA design must allow the suited crewmember to stand and move on terrain with different slope angles and to go up and down the ladder of the Landing Module or Lunar/Martian base. Sand and loose rocks in combination with slopes will be encountered. While walking on uneven terrain, the crewmember may fall and injure himself. That is why, the protective measures listed below will be required in the PSS:

- Restriction of ankle joint mobility in order to prevent dislocation of the crew member’s ankle joint
- Use of dedicated pads inside the suit enclosure (e.g. on knees) to take kneeling position without any pain
- Use of rigid over-boots toes to prevent injures if the suited crewmember drops anything on his feet
- Use of soft pads for chin and forehead in the helmet and/or pads-inserts on the headset.

The PSS design must be coordinated with the mobile transportation system. The PSS design must support use of Moon/Mars rovers, on the one hand, but on the other hand, the Moon/Mars rovers must be designed with the PSS specific features taken into account. For different types of rovers, various means to seat the suited crewmember and provide access to the controls are possible. It is also necessary to foresee the possibility of the Moon/Mars rovers’ failure resulting in the astronaut/cosmonaut returning to the base/landing module without using of any transportation equipment. In this case, the maximum allowable distance between the Moon/Mars rover and base must be determined, taking into account the fact that the suited crewmember will have to return to the base on uneven terrain.

The members of the Martian expedition or lunar base occupants will have different anthropometrics and this fact must be kept in mind in developing the PSS design concept. It is necessary to provide PSS enclosure fit sizing over the required anthropometric range and/or selection of the optimal number of the suit component standard sizes. In the case of a lunar base, crew changes may make it desirable to resize the

PSS for a significantly different build. This can be accomplished if standard sizes of the PSS enclosure components are replaced by others and/or length readjustment is possible. These operations should be easy and should not take much time.

The lifetime of separate components of the PSS (which will be worn out in the process of PSS operation) and the possibility of repairing them are of great importance for these future EVA missions. The PSS should be designed in such a way as to radically decrease the time for its maintenance/repair. PSS maintenance/repair should be performed with the help of standard kits of tools (the possibility of PSS maintenance/repair without any tools is also considered). It is necessary to study consequences of probable damage to different parts of the suit enclosure and take them into account while developing the PSS and working out the test program.

In order to optimize the mass of the PSS system, the mass of the PSS enclosure should be as low as possible. This will provide the greatest crewmember performance capability and enable walking over the uneven terrain of the planet. Moreover, the PSS enclosure should have overall dimensions as small as possible in order to retain the best maneuverability of the suited crewmember working in restricted areas and for easy storage onboard the spacecraft. The PSS mass value for the Mars conditions is more critical than for lunar missions due to the higher level of Mars gravity.

The gravity value influences specific features of the suited crewmember's locomotion. The character of motion may be different: a crewmember can walk, hop, jump etc. Suited walking differs from walking without a space suit. The effects of the positive pressure in the space suit and of a heavy backpack on it interact strongly. Tests performed in ground facilities allow us to evaluate some specific features of the suited crewmember's motions carrying the load. Under reduced gravitation, the presence of the heavy space suit system makes crewmember movements more confident [2]. One of the PSS enclosure objectives is to bear the space suit weight in the vertical position. For confident movement without excessive effort, the relationship between space suit system mass and pressure forces must be optimized.

The PSS LTA is of a great importance in solving this problem. On the one hand, the bending torque of the LTA joints should be minimal in order to decrease metabolic rates for motion, but on the other hand, the LTA legs should not "break" in order to facilitate the crewmember's ability to bear the PSS weight.

It is evident from tests performed at the Zvezda facility (simulation of the Moon gravitional level, 1/6g) as well as from the Apollo expedition to the Moon that under reduced gravitation the crewmembers' lower limbs' joints are flexed [2, 6]. Analogous data were obtained during motion in water, where the test subject weight decreases [3]. Under 1/6g, the test subject posture corresponds to the posture presented in Fig. 1. Under Mars conditions, where the gravitation is 1/3g, the joint flexion angles are approximately the same as those on the Earth for the man in a standing position. During testing in the "lunar" test facility it was also revealed that the suited crewmember's metabolic rate level decreased when he matched the rate of his locomotion to the frequency of oscillations of the "man-suit-backpack with LSS" system.

The PSS enclosure construction must allow the suited crewmember to rise/stand up after falling. Tests performed both in Russia [6] and the USA [8, 9] show that prior to rising/standing on a level surface, the suited crewmember must take a prone position. When tested at the Zvezda test facility (1/6g), the suited crewmember was able to stand up by proceeding through the following motions: pushing off with his hands and moving his torso backward to a kneeling position and rising from the kneeling to the standing position by any of several techniques.

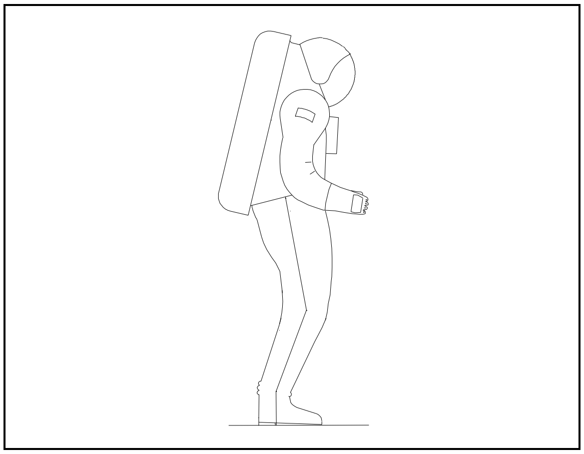

Figure 1. Neutral suited crewmember posture 1/6g

Analysis of the PSS enclosure design concept

Possible design concept of the PSS enclosure: The following design concepts are possible for the space suit enclosure:

- rigid type (all the space suit enclosure components, excluding gloves, are rigid);
- semi-rigid type (hard torso, soft legs/arms);
- soft type (the space suit enclosure made of elastic fabric).

Table 2 presents the comparative mass budget of the well-known EVA space suits, the design of which could serve as a prototype for the PSS.

As it is evident from Table 2, a rigid type suit is the worst option for the Martian suit due to its large mass, as the mass is one of the most critical factors for selection of a suit for use

Table 2 Comparative data on EVA space suit mass (without LSS).

Country	SS	Operating pressure, kPa	Enclosure weight, kg	Remarks (enclosure type)
USA [8, 9]	Apollo	26.2	22.2	soft
	Shuttle EMU	29.6	49.9	semi-rigid
	AX - 5	57.2	77 ... 86	rigid
	MK - III	57.2	58.5	semi-rigid
	I -Suit	26.9 (TBD)	29.5	soft
Russia [6]	Orlan - M	40	30	semi-rigid
	EVA-2000 mock-up	40	25	semi-rigid

Note: Various weights of the AX-5 enclosure depend on the suit size.

on Mars. In Mars' gravitation conditions rising (without any assistance) after falling is impossible if the suit mass is too large. Moreover, the rigid type suit has the largest overall stowage dimensions.

Many years ago for lunar expeditions, Zvezda developed the Krechet space suit of a semi-rigid type with a rear entry hatch. The advantages of such a suit were proven during tests in ground test facilities under Earth gravity and in conditions simulating lunar gravity (1/6g). The Krechet lunar space suit is the prototype for the low Earth orbit Orlan-type suit. For this purpose, the Krechet space suit structure was modified and adapted for orbital use. On this basis, we believe it is reasonable to compare the Orlan-M space suit with space suits developed for planetary exploration. The difference between the masses of soft type suits and semi-rigid suits can be insignificant, however, experience has demonstrated significant advantages of the Orlan design approach. Nowadays the majority of the suit designers in the world understand that a space suit with a rear entry provides a number of advantages over space suits with other entries. We are of the opinion that the development of the space suit on the basis of a semi-rigid type suit with a rear entry is an optimal approach to perform EVAs in orbit, on the Moon and on Mars [11].

Selecting the PSS enclosure design concept, the Zvezda specialists proceed from the conclusion that a semi-rigid type suit featuring a rear entry is an optimal space suit version. A space suit of this type (with HUT) has the following advantages:

- Quick space suit donning/doffing
- The possibility of replacing the space suit arms and LTA easily
- A minimal number of standard sizes
- The possibility of using an airlock of minimal dimensions by connecting the suit back to the module hatch.

A space suit with a rear entry gives a unique opportunity for a crewmember to perform suit donning/doffing without entering a habitation or recovery module by connecting the space suit rear entry to the hatch of the module. In this case, penetration of dust and "alien" microorganisms into the spacecraft is eliminated. Moreover, it is possible to develop lunar/Martian rovers with a pressurized cabin, where the space suit entry connection to the lunar/Martian rovers is also possible [6]. Fig 2. presents the configuration of the semi-rigid type suit enclosure.

The PSS HUT with an entry hatch: The PSS HUT defines to a considerable degree the PSS architecture/mass. The location and dimensions of the entry hatch, angles of shoulder (scye) bearings' inclination and locations of neck/waist interfaces are of great importance for the PSS characteristics (see fig.3). As the PSS HUT entry hatch dimensions have a great effect on the PSS HUT mass, we present an analysis of these dimensions.

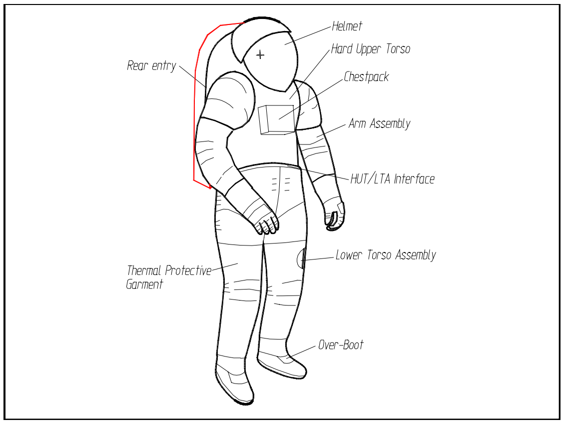

Figure 2. Architecture of semi-rigid type suit enclosure

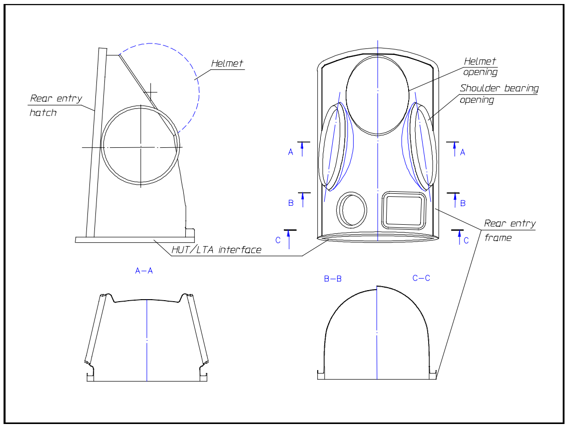

Figure 3. Hard Upper Torso

The frame of the space suit HUT entry hatch is a load-bearing component of the HUT. It must be rigid and made of metal. Locks, hatch hinges, closing system and sealing system are attached to this frame. Moreover, the HUT entry hatch frame is the largest HUT assembly, since a cosmonaut must pass through it. Therefore, it is natural that the HUT mass is primarily determined by the space suit HUT entry hatch dimensions. In order to determine the minimum dimensions of the entry hatch frame, an analysis of dimensions of space suit hatches with a rear entry is presented below.

At present, there are widely varying rear entry height/width relations in different space suits with a rear entry. It goes without saying, that the larger the dimensions of the rear entry, the easier ingress/egress, but as the overall dimensions become larger the space suit mass increases.

The width of the entry is mainly defined by hip breadth with the underwear and LCG taken into account but it isn't defined by the biacromial width, as it may seem at first sight. The dimensions of the human biacromial width are dynamic and can be changed. Having stretched the arms forward or having turned the shoulders, the crewmember can pass through a hatch, the dimensions of which are smaller then the normal biacromial width. Besides the entry hatch, there is another critical element for passing the crewmember through the hatch, that is the arrangement of shoulder bearings but, for brevity, this will not be discussed in this paper.

The design concept of the LTA is the main parameter in defining the entry hatch height. If the entry hatch is long, and consequently the HUT is long, the LTA waist will be short. A long HUT allows convenient arrangement of the controls on the chest pack of the suit. If the waist joint length and/or the space suit anthropometric range increase, it is necessary to make the HUT shorter. In this case it should be taken into account that it will be more difficult to get into or out of the lengthened part of the LTA. The authors of this report have analysed the entry hatches of the existing suits based upon the experience gained in development and operation of the Orlan-type suits. Proceeding from the requirements for PSS HUT mass (the smaller, the better), Zvezda's experts propose the optimal dimensions (in their opinion) of the space suit HUT rear entry. Table 3 presents dimensions of entry hatches of different EVA space suit with a rear entry.

Selection of the optimal minimal rear entry hatch dimensions with easy donning/doffing taken into account will allow the designers to decrease the space suit mass in comparison with existing designs. The space suit HUT mass also depends on selection of materials and technology, but while the HUT enclosure can be made both from metal and fabric, the HUT frame and flanges can be made only from metal.

Table 3. Dimensions of space suit rear entry hatches

Dimension	**EVA SS**				
	Orlan-M	**EVA-2000**	**AX-5**	**MkIII**	**PSS**
Entry hatch height, mm	788	724	700 (TBD)	584 (TBD)	600 (TBD)
Entry hatch width, mm	390	454	432 (TBD)	457 (TBD)	400 (TBD)

The LTA/HUT interface design: The LTA/HUT interface is a fixed sealing disconnect. Waist interface structure selection primarily depends upon the necessity and required number of LTA disconnections/connections during PSS operation.

Using a space suit with a rear entry, LTA/HUT interface connections may be performed several times for the whole operational life. That is why, it is appropriate to use an interface of simple design without a quick disconnect. Such an interface can be made as a flanged connection with the sealing (which is a part of LTA bladder) between the connected LTA/HUT flanges tightened with bolts (see fig.4).

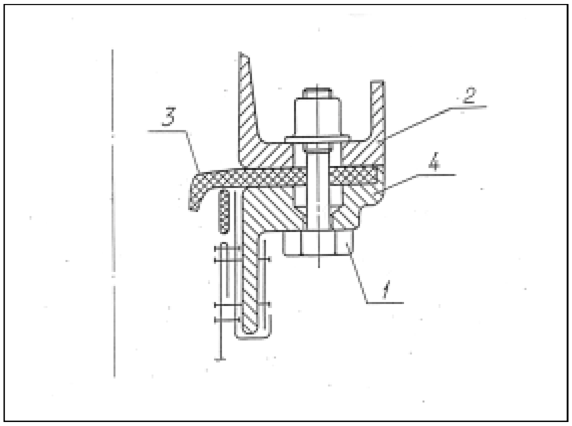

Figure 4. LTA/HUT interface

1. Bolt, 2. HUT flange, 3.LTA bladder as sealing, 4. LTA flange

Using standard tools, a crewmember can replace one size of the LTA with another one in 10-15 minutes (all the activities are performed inside the spacecraft).

The important features of the LTA/HUT interface are its configuration and dimensions providing for space suit donning/doffing. The crewmember hip dimensions including underwear thickness, the LCG and ventilation tubes are determinative.

Location of the LTA/HUT interface in the proposed semi-rigid suit enclosure will be determined by waist joint motion (providing torso bending) and the length adjustment range of the LTA waist. The HUT length should be as short as possible since a long HUT decreases the length of the LTA waist and, as a consequence, the waist joint range of motion as well as the space suit anthropometric sizing range are reduced.

Determination of the PSS/LTA joints/bearings list

Types of joints/bearings: Various types of joints have been developed. In our concept for the PSS enclosure it may be desirable to use a combination of the soft-type joints (all fabric technology) and bearings with further modification and adaptation to the PSS purposes. Two types of joints are in current use: joints with fabric flat pattern gores and with convolutes. Design optimization parameters for these joint types for the PSS are different from those for current orbital applications and ma lead to new implementation details and material choices for improved performance.

Research and experience gained in operation show that the space suit soft joints (having the same range of bending angles as rigid-type joints but having greater torques) have the following essential advantages over rigid-type (rolling convolute) joints:

- Simplicity of the joint technology
- Small weight
- Small overall dimensions in a folded state (during stowage)
- Resistance to dust
- Long useful life
- Easy to maintain.

Proceeding from the requirement to minimize the PSS mass, it is desirable to find an optimal compromise in combining bearings and soft joints. Different combinations of joints/bearings can be used in the suit enclosure. A great number of bearings are used in some space suits; however, such a design has significant mass and overall dimensions. In our opinion, an optimal compromise on bearing usage should be found through comparative testing of a space suit with bearings and space suits with other design arrangements. For example, in the AES suit and I-suits, an oblique hip bearing, a convolute joint (for adduction/abduction) and a thigh bearing were used for hip/thigh mobility, while in the "Krechet" lunar space suit, two convolute joints are used. In the Mk III space suit, three oblique hip bearings with a joint for adduction/abduction are used.

The specific features of the PSS LTA joints' operation depend on the fact that these joints are not only "extended" under positive pressure (as in case of orbital space suits), but they are also "compressed" under the space suit HUT assembly weight. The greater the space suit mass and gravity, the greater the influence of this factor.

Besides joint dynamic bending torque values, the metabolic work rate of the suited crewmember depends on the following:

- Forces to retain joints in a bending position (static torque)
- Space suit joint/human joint misalignment (i.e. lack of coincidence of the space suit joints and human limbs' motion kinematics)
- Joint bending smoothness; absence of jerks and abrupt changes from one joint position into another.

The waist joint features instability and the most significant forces (to retain bending position) in comparison with other joints. For example, waist joint instability has been reported for the rolling convolute waist joint on the Mark III space suit, ([9], see section "Results", paragraph "Mk III Hybrid Suit" where it is noted: "The subject also reported instability in the waist rolling convolute feature"). Space suit joint/human joint alignment is achieved by sizing the space suit enclosure to the crewmember by varying the enclosure length between joints. Motion smoothness is achieved by introducing devices, the function of which is based on the friction force.

In the PSS, the availability of hip, knee and ankle joints (at minimum) is necessary. In the sixties this was implemented in the lunar space suits of the USA/Russia. In the PSS LTA the followings joints/bearings can be used (beginning from the waist interface, one after another):

- Waist bearing (torso rotation)
- One-degree-of-freedom waist joint (torso flexion/extension)
- Two-degree-of-freedom waist joint (torso flexion/extension, abduction/adduction)
- Two-degree-of-freedom soft hip/thigh joint (thigh flexion/extension and abduction/adduction)
- Hip bearings, (2-4 for each leg) located at angle to one another (thigh flexion/extension and abduction/adduction, torso rotation); these hip/thigh bearings can be used in combination with a joint for adduction/abduction
- Bearings (1 piece for each leg) located on the thighs higher the knee
- Knee joint (flexion-extension of legs in the knee)
- Calf bearing, 1 piece for each leg (torso rotation, foot rotation)
- One-degree-of-freedom ankle joint (foot flexion/extension)
- Two-degree-of-freedom ankle joint (foot flexion/extension and abduction/adduction).

It is necessary to mention that a one degree of freedom hip/thigh soft joint (space suits: A7LB, EMU, Orlan) was not included in the above presented list, as in our opinion, such a joint will not satisfy PSS mobility requirements. The analysis of the PSS LTA joints/bearings is presented below.

Waist bearing: Based on the results obtained during testing performed at Zvezda, one can conclude that bearings are necessary in order to enable efficient suited walking and to improve the over all space suit control. Leg bearings (thigh or calf) allow torso rotation in a vertical position (standing or walking, but when the knees are bent, bearings in the space suit legs support little or no upper torso rotation. Important cases where this applies include:

- Kneeling
- Sitting while driving a rover.

When the suited crewmember's knees are bent, the upper torso can rotate only with the help of a waist bearing. In collecting samples, torso rotation enabled by the twist in the spinal column helps the suited crewmember to reach the ground. A waist bearing is essential to support this motion in a pressurized space suit. In spite of the fact that the waist bearing has certain shortcomings, (such as large weight, size and break-away torque), analysis of the test results shows that the waist bearing improves walking quality and helps the suited crewmember to retrieve rock samples. This analysis supports the conclusion that a waist bearing should be used in the PSS.

Waist joint: The waist joint can have one or two degrees of freedom. Joints of both types have been developed.

Use of a two degree of freedom waist joint (AES and ZPS) in order to provide torso abduction/adduction results in complication of the space suit sizing plan, since the development of several standard sizes of the waist module will be required. This will lead to an increase in system mass. A waist joint with one degree of freedom is more easily integrated in the space suit enclosure. This joint is better able to perform one of the important functions of the PSS enclosure, forward flexion. Experience gained in development and testing at Zvezda shows such a joint (one degree of freedom waist joint) helps the suited crewmember to take a sitting posture. We believe that a one degree of freedom flat pattern waist joint should be used in the PSS. This joint (see Fig. 7) provides for the suited crewmember's waist flexion. Above, it is bounded by the HUT waist interface and/or by the waist bearing. A lower ring serves as a restraint component and is installed to hold the waist joint convolutes. To decrease the joint volume, the waist joint cross-section should be elliptical. A restraint component (a strap with a rigid guide passing through the LTA crotch) is attached to the lower ring. To fix the waist joint during flexion/extension, the waist joint central strap can move in the LTA crotch (along the guide), providing smooth joint motion without any jerks. All the straps can have buckles to adjust the length of the PSS enclosure waist.

Hip joints: The mobility of hip joints of the Apollo space suit was less than desired [3, 8, 9]. This shortcoming can be eliminated in a next-generation PSS. In the sixties during the development of the Russian lunar space suit, a two degree of freedom hip/thigh joint was developed and tested. This joint provided thigh flexion/extension, torso- forward bending and thigh abduction that resulted in improvement of the cosmonauts' lateral stability (see Fig. 5).

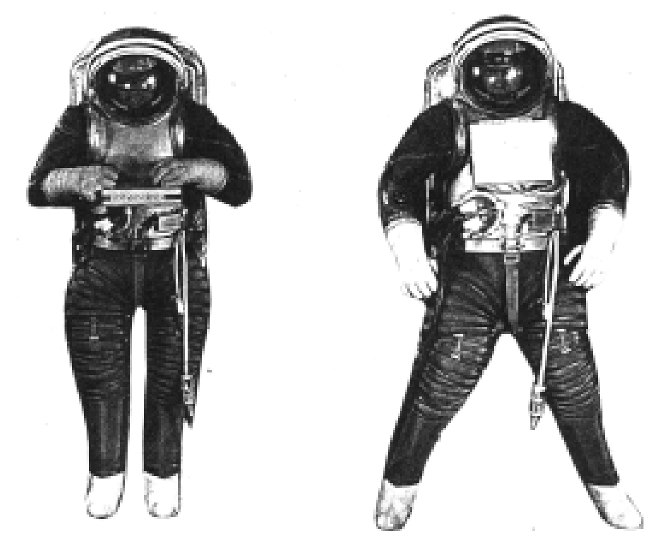

Figure 5. Krechet Lunar Suit

Currently, space suits with several hip/thigh bearings also have sufficient mobility, but such design solutions result in a mass penalty. Table 4. presents comparative characteristics of rigid and soft type hip joints.

Table 4. Hip joint design characteristics

#	Characteristic	3 bearing hip	Soft two degree hip/thigh joints
1	Mass	2	1
2	Volume (while stored)	2	1
3	Efforts for walking (force value)	1	2
4	Standing on a knee	2	1
5	Programmed (natural) movements	2	1
6	Retrieving rock sample	1	2
7	Stability when the torso is bent	2	1

Note:
"1" – the best characteristics; the 1st place.
"2' – characteristics with worse indexes; the 2nd place.

Mk III space suit (with 3 bearing hip) test results show, that subjects reported the effect of the programmed motion in the hips during walking and kneeling. With this in mind, one can conclude that subjects will require training and adaptation to effectively use this kind of hip joint.

It is difficult or impossible to kneel when suited in the Apollo or EMU space suits with soft hip/thigh joints, but this doesn't mean that suited crewmembers in suits with soft joints of different design will not be able to comfortably complete such a movement. Figure 6 shows a space suit mock-up developed by Zvezda in 1969. The suited test subject is in kneeling posture; the suit pressure is 0,4 atm.

Figure 6. Kneeling in a pressurized suit

Based on the tangible advantage of reduced PSS enclosure mass, a soft, two degree of freedom, soft hip/thigh joint is proposed. In order to provide two degrees of freedom for the LTA thigh, a soft joint with a rigid gimbal ring can be proposed (see Fig. 7). Use of a bearing below the thigh joint is possible. It may also be advantageous to study a combined hip- waist joint using soft joint technology.

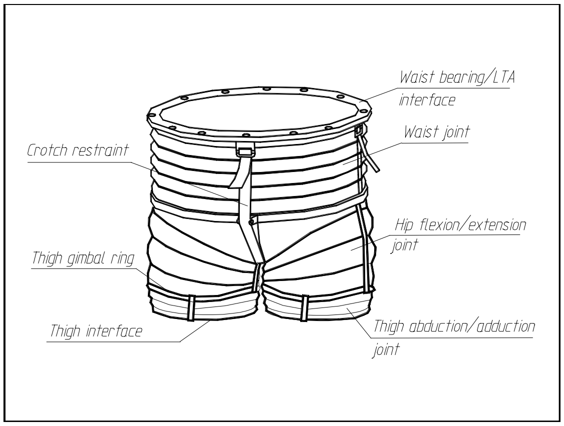

Figure 7. Waist and hip/thigh joints concept.

Knee joint: In the process of suited walking, the knee joint range of motion is 50...90° [6, 7]. However, in selecting the range of motion for the knee joint, it is necessary to take into account the angles necessary for other activities as well. In case the suited crewmember falls, the necessary range of motion increases to a considerable degree in order for the suited crewmember to get up. When he is rising to a standing position, the required range of motion of the knee joint significantly exceeds values observed during walking. The knee joint is proposed using flat pattern gores. The circumferential dimensions of the flat pattern gored joint are smaller than those of the convolute joint

Calf bearing: Using calf bearings provides:

- Space suit torso rotations in a standing position without foot movement;
- Right, left, and 180° turns in place;
- Easy change of direction when walking (avoiding obstacles);
- Retention of a stable posture (stable equilibrium) in uneven terrain (the foot takes the most stable position on the slope).

The calf bearings can be combined with disconnects, which can be used to connect/disconnect the boots. Introducing calf bearings into the PSS for exploration of the Moon and Mars will enable cosmonauts to decrease metabolic rates while translating on the surface of these planets.

Ankle joint: In the sixties for lunar exploration, the A7LB (ILC, USA) and Krechet (Zvezda, Russia) space suits were developed, in which one degree of freedom soft ankle joints were used. The joints were simple in their design and enabled test subject ankle flexion/extension over the necessary range of motion. As a consequence, the suited test subject could walk on the supporting surface of test facilities and/or on the lunar surface. In modern EVA space suits (EMU and Orlan-type suits), one-degree-of-freedom soft ankle joints are used as well.

In the late sixties during testing of the Krechet lunar space suit at Zvezda, introduction of two degree of freedom ankle joints into the space suit enclosure (to provide human ankle pronation/supination) proved to be advantageous. This additional degree of freedom assists the crewmember in maintaining stability and equilibrium while he is standing on a slope.

The two-degree-of-freedom ankle joint provides:

- Stable position of the suited crewmember on the slope with his side toward the slope and translation on the inclined surface
- Pronation/supination of the subject's ankle joint when his boots' soles step on uneven planetary terrain
- Pronation/supination of the feet while driving a Lunar/Martian rover.

When the crewmember takes the position "side towards the slope", the pronation/supination capability of the ankle joints allows the suited crewmember to walk safely on steeper (by 10°) slopes [6].

In the process of walking, the ankle joint adjusts the foot position. Even small angle motions of the ankle joint are very important for maintaining lateral equilibrium. While walking, the pronation/supination range of motion usually does not exceed 10°, but enabling this motion is of great importance in increasing the crewmember lateral stability. Experience highlights the need to optimize the balance between ankle abduction/adduction capability and ankle support [10]. In order to prevent human ankle dislocations, the range of motion of the PSS ankle joint shall be limited.

Integration of a boot providing ankle rotation, biaxial ankle flexion capabilities and flexible boot sole provide significant benefit for walking mobility on a planetary surface in terms of personnel comfort, security and walking speed over uneven and sloping terrain [10].

An ankle joint with a gimbal ring is proposed for the LTA (see Fig.8) to provide two degrees of freedom for the ankle joint. A gimbal ring with increased bending stiffness can serve as a joint separator for flexion/extension and adduction/abduction.

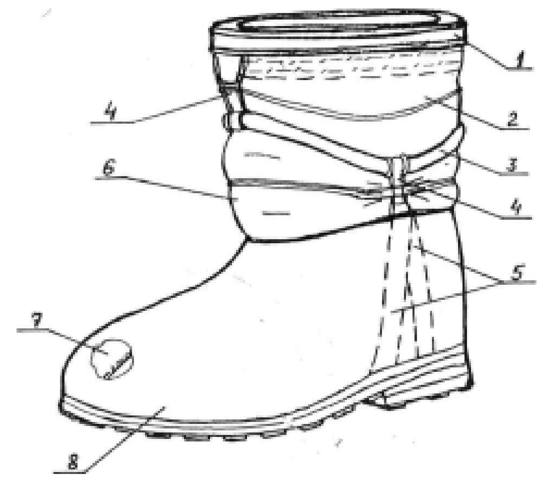

Figure 8. Boot with gimballed ankle joint.

1. Calf bearing, 2. Adduction/abduction ankle joint, 3.Gimbal ring, 4.Axial restraint line, 5.Restraint webbing, 6.Flexion/extension ankle joint, 7.Boot's restraint layer, 8.Protective over-boot.

PSS LTA Design Concept: Based on the analysis performed, the following list of the LTA joints/bearings (see Fig.9) is proposed for the PSS:

- Waist bearing
- One degree of freedom convolute waist joint located between the waist interface and lower ring with crotch rolling restraint
- Two degree of freedom soft gimballed hip/thigh joints,
- Thigh bearings (TBD)
- Knee joints with flat pattern gores
- Calf bearings
- Two degree of freedom gimballed soft ankle joint.

Zvezda places emphasis on the consideration of a combined fabric waist/hip joint as a possible alternative for the PSS enclosure, able to replace the waist/hip joints and bearings mentioned above.

With respect to the LTA mass, the mass of the Orlan-M LTA is not more than 7.8 kg; the mass of the EMU LTA is 21.8 kg. Taking into account the experience gained in space suit development over 40 years, there are grounds to suggest, that the PSS LTA mass can be 10-15 kg in accordance with our preliminary assessment.

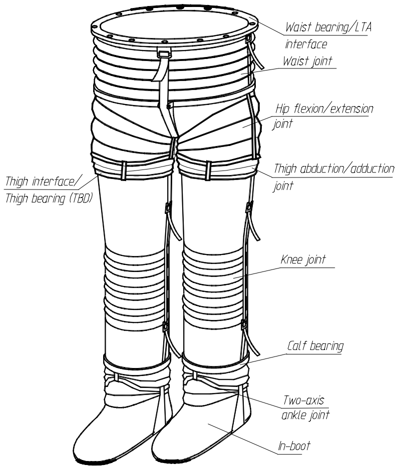

Figure 9. PSS LTA design concept.

Other factors impacting the PSS enclosure design

Among other factors impacting the PSS enclosure design concept it is necessary to note the following: comfort provision and dust protection.

Comfort provision: While walking on planetary surfaces, the crewmember's body will intensively interact with the suit enclosure. This fact calls for application of dedicated soft insert/pads in the LTA design in order to prevent pressure/squeeze points, rubbing, etc. on the crewmember's body. The arrangement of the insert/pads can be:

- On the LTA inner surface
- On the underwear/LCG donned directly on the suited crewmember's body
- A combined arrangement of both of these.

Comfort of the crewmember wearing the suit (intended for exploration of the Moon/Mars) depends to a considerable degree on the footwear, its mass and the availability of custom inserts/profiled insoles. The restraint of the foot within the boot must be optimized in order to transfer lateral loads into the foot comfortably[10].

Figure 10 presents the LTA with assumed places of inserts/pads arrangement. Convenient inserts can be made detachable, allowing the suited crewmember to replace them as desired with inserts of other types (in thickness, stiffness, shape and size). Soft insert/pads can also be used in a helmet or on the headset (for example, in the chin/forehead area).

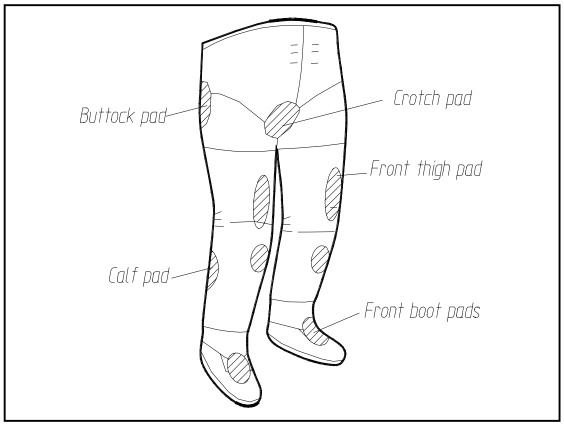

Figure 10. The proposed LTA comfort pads arrangement.

Dust Protection: The presence of dust on the Moon/Mars surfaces is one of the environmental factors, which is not observed in near-earth orbit during EVA. The Moon/Mars dust composition as well as dust particle sizes are well known.

During walking on the planetary surface dust can deposit on the outer TMG. Some dust can reach the suit enclosure. Should the dust penetrate to the suit enclosure, it will penetrate into the Planetary Base/Landing Module. Procedures for cleaning dust from the PSS are needed. It is also necessary to perform additional tests for the definition of dust influences on suit components.

The PSS enclosure soft components, made of fabric (such as webbings, cords and fabric of the restraint layer), can have a dedicated saturant capable of protecting the fabric from dust, i.e. preventing absorbing it. It is evident, that the most critical PSS enclosure assemblies in terms of dust penetration are bearings. In order to eliminate penetration of dust into the bearings, dedicated dust seals will be required [4].

Conclusions

As the result of this study of the PSS enclosure concept, the design of a semi-rigid type suit with a rear entry is proposed.

The LTA is one the most critical assemblies of the PSS enclosure. For the LTA, a special analysis of joints/bearings has been conducted. A comprehensive assessment of the PSS LTA movable joints (providing for crewmember activity on the planetary surfaces) has been performed, and this report presents results of the study.

It is evident from the study performed, the most critical assemblies of the PSS LTA requiring the greatest attention and study at present are the waist/hip joints and their combinations.

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