THE NATIONAL CENTER FOR MICROGRAVITY RESEARCH

NCMR

FLUIDS AND COMBUSTION

Final Report to STAR Enterprises

For Work Performed in Support of the

Advanced Animal Habitat – Centrifuge (AAH-C)

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1 Executive Summary

The National Center for Microgravity Research on Fluids and Combustion (NCMR) entered into an agreement with STAR Enterprises, Inc. and Space Hardware Optimization Technology, Inc. (STAR-SHOT) in which NCMR staff scientists Drs. Jeff Allen and John Kizito rendered expert advice on the management of biological fluids for the Advanced Animal Habitat - Centrifuge (AAH-C). The AAH-C is being developed to house rats, and possibly mice, on the International Space Station (ISS) for the conduct of biological research. Dr. Allen and Kizito were contracted to help engineers design a habitat which would keep the rodents dry and healthy during the low-gravity mission. The statement of work for the initial contract included the following tasks:

1. measuring the transport properties of rodent urine,
2. cooperatively developing a concept of managing fluids within the specimen chamber such that:
   (a) the animals remain suitably dry,
   (b) fluids within the specimen chamber are directed to the primary waste filter and/or liner for containment and/or evaporation,
   (c) fouling of the lighting subsystem, the camera lenses, and sensors within the specimen chamber is minimized,
   (d) liquid is deterred from entering air outlet, and
3. cooperatively developing a plan for concept verification.

After the initial four month contract period had expired, the contract was extended and expanded to include the additional task:

4. support and participate in the Advanced Animal Habitat PDR. NCMR will present the findings on the physical properties, the low-gravity fluids management concept, and the concepts for prevention of fouling of the lighting, video, and air exchange subsystems.[1]

Dr. Kizito and several undergraduate students measured the physical properties of rat and mice urine. The measured properties were primarily the static contact angle, surface tension, viscosity, and density, but other properties were measured as well. The data from these measurements is included in Appendix E in the form of two reports.

Support provided by NCMR on the second task listed above included a variety of activities. First, a workshop on the behavior of liquids in a low-gravity environment was conducted by Drs. Allen and Kizito at the SHOT facility on February 16, 2001. The purpose of the workshop was to instruct the engineers at STAR-SHOT on what is and what is not known about capillary flows and low-gravity fluid management. NCMR's support on the second task also included recommendations for the design of the Science Evaluation Unit (SEU). The purpose of the SEU was to expose potential principal investigators (PI's) to the types of animal interfaces anticipated on the AAH-C and to get feedback from the PI's for design iterations.

The bulk of the support provided by NCMR on task 2 involved a feasibility study of the "corrugated liner concept" developed at SHOT. The corrugated liner concept is a box-like habitat in which four of the sides are grooved so as to wick liquids toward a fifth wall which

[1] The Preliminary Design Review (PDR) for the AAH-C was canceled because of funding cuts and all work on the AAH-C has been suspended as of October, 2001.

is a waste filter (see Figure 2). Drs. Allen and Kizito evaluated this concept to determine if the waste fluids (water and urine) could be transported via capillarity the length of a wall to the waste filter. The results of the feasibility study are discussed in §4. To summarize, the concept may work as long as debris does not trap liquid in the grooves and as long as the waste filter does not become impermeable at the groove junction. Both the effect of debris in the grooves on liquid trapping and liquid flow at the waste filter/groove junction require further investigation. Recommendations for concept verification (task 3) are also presented in §4. Finally, alternatives to the corrugated liner concept for the liquid management in the habitat suggested by NCMR are discussed in §5.

2 Introduction

The objective of the collaboration between the National Center for Microgravity Research on Fluids and Combustion (NCMR) and STAR Enterprises was to tap the expertise in low-gravity fluids management at the NCMR to assist in designing a suitable habitat for rodents on the International Space Station (ISS). Previous animal habitats had functioned unsatisfactorily primarily due to mismanagement of waste fluids. The most obvious problem being that the animals became soaked in urine and water; leaving them distressed and/or very ill or dead. In order to conduct biological experiments, healthy animals are required. Therefore, STAR Enterprises contracted the NCMR to assist in the design of a habitat which would manage liquids in low gravity such that the animals (rats and mice) would not become distressed or ill due to contact with waste fluids.

2.1 Statement of Work

The complete statement of work for the initial contract period between NCMR and STAR-SHOT in the development of the Advanced Animal Habitat (AAH) is in Appendix B. The objectives of that contract may be summarized as:

1. *measuring the transport properties of rodent urine,*
2. *cooperatively developing a concept of managing fluids within the specimen chamber such that:*
   (a) *the animals remain suitably dry,*
   (b) *fluids within the specimen chamber are directed to the primary waste filter and/or liner for containment and/or evaporation,*
   (c) *fouling of the lighting subsystem, the camera lenses, and sensors within the specimen chamber is minimized,*
   (d) *liquid is deterred from entering air outlet, and*
3. *cooperatively developing a plan for concept verification.*

After the initial four month contract period had expired, the contract was extended and expanded. The complete proposed statement of work for the contract extension is presented in Appendix C. The extended contract included the original objectives listed above as well as an additional task:

4. *support and participate in the Advanced Animal Habitat PDR scheduled to be conducted in August, 2001. NCMR will present the findings on the physical properties, the low-gravity fluids management concept, and the concepts for prevention of fouling of the lighting, video, and air exchange subsystems.*

The following sections describe the activities of NCMR staff, relative to this agreement, over a twelve month period. A summary of the physical property measurements of rat and mouse urine are presented in §3. The measurement technique and the complete set of data is included in Appendix E in the form of two reports. Evaluation of the STAR/SHOT corrugated wall concept as it pertains to management of waste fluids in low gravity is discussed in §4. The calculations used in the technical evaluation are included in Appendix D. Alternative concepts to that of the corrugated wall are introduced in §5.

In addition to making physical property measurements and evaluating habitat designs, NCMR staff also provided two additional support activities. The first was to conduct a workshop on the behavior of liquids in a low-gravity environment for STAR and SHOT. The second was to provide recommendations on the Science Evaluation Unit.

2.1.1 Seminar on Behavior of Liquids in Low-Gravity

A workshop on low-gravity fluids management was conducted at SHOT on February 16, 2001. The workshop included a discussion on the state of knowledge of capillary behavior; e.g. what is known and what is not known about low-gravity fluid behavior. Pertinent scaling parameters and guidelines for evaluating engineering designs relative to low-gravity fluids management were also discussed. The intent of the workshop was to teach the STAR/SHOT scientists and engineers capillary phenomena in order to reduce the number of design options being considered. The physical property measurement techniques and some preliminary findings from the property measurements were also presented.

2.1.2 Recommendations for the Science Evaluation Unit

The Science Evaluation Unit (SEU), as understood by NCMR, was intended for use by the principal investigators (PI's) for ground-based experiments in order to gain experience with the types of interfaces anticipated for the Advanced Animal Habitat (AAH). In addition, STAR was to gather feedback on the interfaces from the PI's so as to improve the functionality of the flight unit. NCMR provided conceptual designs recommendations for the Science Evaluation Unit (SEU) to STAR. The recommended concept is illustrated in Figure 1.

NCMR's concept for a Science Evaluation Unit was to allow the investigator to only have visual access to the animals via video and that all systems (water, air, lighting, video, food, etc.) would be subject to the effects of urine, feces, foodbar particles and other debris. To that end, the design concept was a horizontal cylinder with the ends and the top constructed from an opaque material (sheet metal) with the bottom half of the cylinder being fabricated from a wire mesh (see Figure 1). All animal interfaces, such as air flow, water, food, lighting and video, would have to be directed through the bottom wire mesh of the habitat and, thus, would be exposed to all of the debris and waste fluid of the habitat. In addition, the cylindrical shape would help the PI's get accustomed to the animals occupying a volumetric space as opposed to a planar space represented by a cage bottom. In other words, in low-gravity, the animals will move in a three-dimensional space whereas on Earth, in traditional cages, the animals move in a two-dimensional space. Standard video techniques

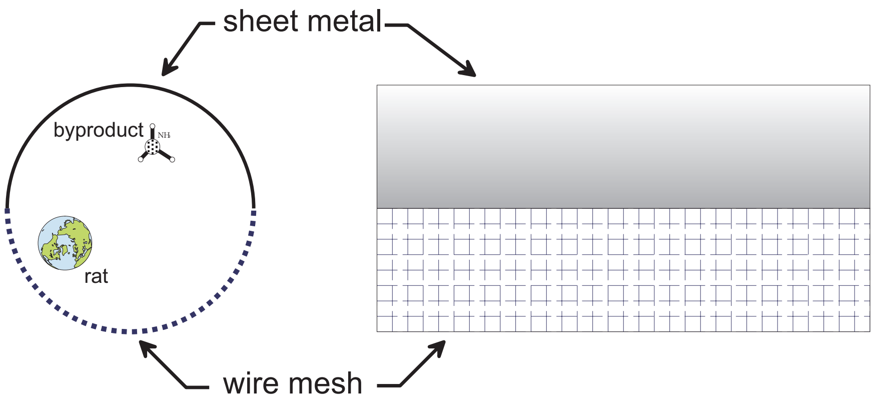

Figure 1: Side and end view of a conceptual Science Evaluation Unit for ground-based investigations as recommended by NCMR. The animal habitat is a horizontal cylinder with the ends and the top half constructed of an opaque material which blocks direct observation of the animal. Thus, the PI must use a video feed for observation; simulating the conditions which will be found on the International Space Station. The bottom of the habitat is constructed from a wire mesh. All of the animal interfaces are directed through the bottom of the habitat thereby exposing the various systems (food, water, lighting, video, etc.) to debris and waste fluids; also simulating conditions found in a low-gravity environment. Finally, the cylindrical shape approximates how the animals, when in space, would not reside on a two-dimensional plane as they do on Earth.

which work for observing animals on Earth may not be suitable when the animals are not confined to a single, horizontal plane. Because of time and budget restraints, the NCMR's recommendation were not implemented in the final design of the SEU.

3 Physical Property Measurements

The results of the physical property measurements for both mouse and rat urine have been provided in two separate reports which are attached in Appendix E. The first report is "Physical Measurements of Rodent Urine for the Advanced Animal Habitat – Centrifuge (AAH-C) Project" dated January – June 2001. This report describes (*i*) the urine samples tested and the collection techniques, (*ii*) the measurement techniques for determining the density, viscosity, surface tension, contact angle hysteresis, contact angle, and evaporation rate, and (*iii*) the results of those measurements for mouse and rat urine. The second report, "Effect of Surface Treatment on Static Contact Angle for the Advanced Animal Habitat – Centrifuge (AAH-C) Project" dated July – September 2001, is concerned with the effect of surface roughness and material selection on the static contact angle. The measurement techniques, data analysis and results are presented for both male rat urine and water at room temperature.

Table 1: Summary of average measured properties of mouse and rat urine. The values reported here for density, viscosity, surface tension, and contact angle are for a temperature of 23 °C. The evaporation rate for mouse urine is at 23% humidity and 23 °C and showed a linear drop in mass over a 30 hour period.

measurement	**mouse**	**rat**
density, ρ (g/mL)	1.050 (male)	0.967 (male)
	1.03 (female)	1.002 (female)
kinematic viscosity, ν (cSt)	1.12	0.99
surface tension, σ (dynes/cm)	46.68	36.47
evaporation rate	3 mg/min	

A summary of the average measured physical properties is presented in Table 1 for reference. The properties listed are average values at a temperature of 23 °C. Static contact angles were measured on various samples with varying surface roughness. The test samples were treated by stone polishing (with 1200 grit), glass bead blasting (with 60-100 grit) and sand blasting (with medium grit sand) to create various surface energies. A summary of the contact angle measurements is given in Table 2.

Table 2: Summary of contact angles of urine or water on various substrates.

	Male Rat Urine			Water		
Treatment	Aluminum	Titanium	Ultem1000	Aluminum	Titanium	Ultem1000
Untreated	67.0	47.7	74.0	56.5	55.0	74.5
Sand-Blasted	18.8	21.3	54.0	76.0	60.0	30.5
Glass-Blasted	43.0	23.5	50.5	62.0	29.6	28.0
Polished	54.0	25.0	42.0	69.5	53.0	44.0

4 Evaluation of the Corrugated Liner Concept

The only mature concept under consideration for the Advanced Animal Habitat (AAH) is corrugated liner concept which is illustrated in Figure 2. Four parallel "side" walls[2] are corrugated, or grooved. A waste filter composes one end of the habitat, the "bottom", and the "top" consists of parallel bars (not shown in Figure 2). The grooves are intended to capture and wick the liquid via capillarity to the waste filter. The waste filter is a permeable substrate which should wick the liquid from the groove. The liquid is primarily urine and water. On the exterior face of the waste filter, external to the rodent habitat, the water is evaporated so as to allow for continued wicking from the grooves and to minimize the down mass. After a predetermined number of days, the waste filter is replaced. This particular design concept is intended for rats and is likely unsuitable for mice because of the properties of mouse urine.

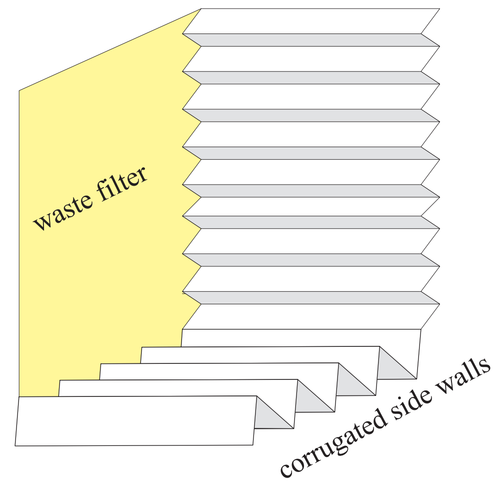

Figure 2: Corrugated wall concept for the Advanced Animal Habitat (AAH). The four "side" walls consist of regular grooves so as to capture and wick liquid to the waste filter. The end of the habitat opposite the waste filter consists of parallel bars (not shown).

As mentioned above, the grooves have multiple functions. The primary purpose of the grooves is to move fluids to the waste filter. A secondary purpose of the grooves is to contain the waste liquids and minimize the exposure of the rats to the captured fluids. Should the waste filter fail due to loss of power or other negative event, this capture-and-contain function of the grooves may be able to keep the rodents suitably dry until the waste filter can be rendered operational again.

In the following sections, the corrugated liner concept has been evaluated for feasibility in (*i*) capturing liquids droplets, (*ii*) holding, or storing, liquids in order to keep the rodents suitably dry, and (*iii*) transporting the urine to the waste filter via capillarity. The discussion of the findings begins with the latter function of the grooves.

4.1 Liquid Transport

The corrugated liner concept requires that the liquid be captured by the grooves and then pumped via capillarity to the waste filter. A specific set of criteria must be met in order for the liquid to be captured and for capillary wicking to occur. In addition, the waste fluid must be wicked at a sufficient rate so as to prevent deposition of urea crystals in the groove as the water evaporates. Optimization of the groove geometry for the most efficient capillary

[2]The designations of "side", "bottom" and "top" for the habitat walls only apply in a gravitational environment; either on Earth or on the space station centrifuge. For low-gravity applications, this nomenclature should not be used since it presupposes an orientation.

wicking is determined by varying the groove half-angle, α.

The geometry of a low-Bond number[3] liquid surface in a groove is illustrated in Figure 3. The groove geometry is defined by the half-angle of the groove, α, and the peak separation of the grooves, ℓ. The geometry of liquid in a groove is defined by the contact angle, θ, the half-angle of the groove, α, and the centerline height of the liquid, d. Specifying α, θ and d allows for a complete characterization of the liquid surface shape and cross-sectional area; see Appendix D.1 for details.

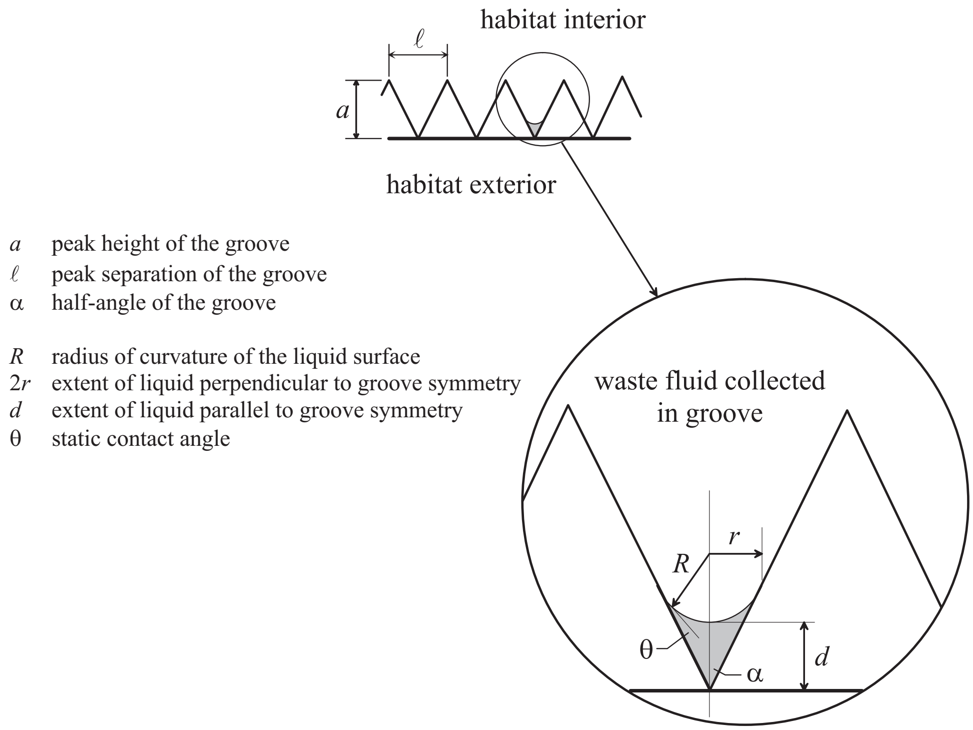

Figure 3: Cross-sectional view of a corrugated wall with a magnified view of the groove which contains liquid. The important parameters for optimizing the groove design are the half-angle, α, the peak height of the groove, a, and the static contact angle, θ.

4.1.1 Optimum Groove Geometry for Wicking

Capillary wicking in a corner will occur only if the Concus-Finn condition is satisfied:

$$\alpha < \frac{\pi}{2} - \theta \quad , \tag{1}$$

[3]The Bond number, Bo, is defined as $\Delta\rho g L^2/\sigma$, where σ is the surface tension of the liquid, $\Delta\rho$ is the density difference across the interface, g is the gravitational acceleration and L is the characteristic length scale of the system. When Bo > 1, gravitational effects determine the surface shape. When Bo < 1, capillary effects determine the surface shape. For an animal habitat in low gravity, the Bond number will be much less than 1.

where θ is the static contact angle. The value static contact angle is a function of both the liquid and the surface of the liner. As shown in §E, the static contact angle may vary significantly depending upon the material chosen for the corrugated liner. For the purposes of analyzing the corrugated liner concept, we chose a poorly wetting system with a static contact angle of $\theta = \pi/4$ (45°). Based on the Concus-Finn condition, the groove half-angle, α, must be less than $\pi/4$. Note, however, that the Concus-Finn criteria is a necessary, but not a sufficient condition. For non-perfectly wetting systems ($\theta > 0$), hysteresis in the *dynamic* contact angle may result in liquid holdup. Since urine will not perfectly wet any suitable substrates for the AAH, the actual value for α should be much smaller than the critical angle as determined by the Concus-Finn criterion.

Equation (1) provides an upper limit for α, but does not allow for determination of the optimum wicking angle of the groove. The optimum wicking angle may be determined from the similarity solution derived by Weislogel.[4] The maximum rate of capillary wicking in a groove may be found by maximizing the value of the spreading coefficient, K:

$$K = \frac{1}{\Lambda^{1/5}} \left[\frac{\sin^2\alpha}{\Psi} \right]^{2/5} \quad ; \tag{2}$$

where Ψ is the aspect ratio of surface curvature, R, to liquid depth, d, and Λ is the liquid cross-sectional area normalized by d^2. The dimensionless parameter Λ is constant along the entire length of the groove provided the static contact angle and the half-angle of the groove do not change. Derivations for Ψ and Λ are provided in Appendix D.1.

The relationship described above is geometric in nature; that is, the fluid properties do not enter into the expressions except through the static contact angle. The values of the spreading coefficient, K, for $\theta = 45°$ and various values of α are listed in Table 3; the maximum value of K occurs when $\alpha = 15°$.

Though the groove geometry can be optimized for wicking, we still have not determined if the rate of wicking is sufficient to move the liquid to the waste filter and minimize evaporation in the groove. As the urine evaporates, urea crystals will be deposited, which, if in the groove, will "plug" the groove to future liquid flow.

The rate of capillary flow may be estimated using the similarity solution derived by Weislogel, et al. [1-3]. His analysis is based on a drop of volume, V, being deposited in a groove at time, $t = 0$. The centerline height of the liquid, d, (see Figure 3) may be determined as a function of time and lengthwise distance along the groove, z:

$$d(z,t) = \frac{C_1}{t^{0.2}} \left[1 - \left(\frac{C_2\, z}{t^{0.4}} \right)^2 \right] \quad , \tag{3}$$

where C_1 and C_2 are constants which depend upon the geometry, fluid properties, and liquid volume. Details of the derivation of equation (3) are summarized in Appendix D.2. For the purposes of this analysis we will use the values shown in Table 4 which are typical for an

[4] Weislogel & Lichter (1996) "A Spreading Drop in an Interior Corner: Theory and Experiment", *Microgravity Science and Technology*, **IX**/3, 175–184. Additional information may be found in the bibliography listed in Appendix A.

Table 3: Value of the spreading coefficient, K, as a function of the half-angle of the groove, α, for $\theta = 45°$.

	$\theta = 45°$			
α (deg)	γ (deg)	Ψ	Λ	K
5	40	0.1406	0.0893	0.5046
10	35	0.3255	0.1828	0.5424
15	30	0.5774	0.2808	**0.5447**
20	25	0.9368	0.3839	0.5269
25	20	1.4855	0.4925	0.4938
30	15	2.4142	0.6075	0.4460
35	10	4.2955	0.7296	0.3811
40	5	9.9937	0.8600	0.2882
45	⟵ critical groove angle			

adult male rat. The contact angle is picked to represent a poorly wetting system ($\theta = 45°$) and the drop volume of 8 μliters is thought to be a relatively large drop of urine (diameter $\approx$ 2.5 mm). Using these values, the constants in equation (3) are:

$$C_1 = 7.715 \times 10^{-4} \ \ \mathrm{m} \cdot \mathrm{sec}^{0.2}$$

and

$$C_2 = 22.28 \ \ \mathrm{sec}^{0.4}/\mathrm{m} \ .$$

Once the droplet is captured by the groove, equation (3) describes the height of the liquid surface at any z along the groove at any time. If d, α, and θ are known, then the liquid surface shape and cross-sectional area are completely described (see Appendix D.1).

Table 4: Test conditions used for calculations of capillary-driven flow in a groove. Fluid properties and the static contact angle are typical of male rat urine at room temperature.

density, ρ	967 kg/m^3
viscosity, μ	0.957 cP
surface tension, σ	0.0365 N/m
static contact angle, θ	45°
half-angle of groove, α	15°
drop volume, V	8 μliters

Using the values specified in Table 4, the liquid height is plotted as a function of position along the groove and time in Figure 4. An 8 μliter drop of urine wicks in the groove very rapidly; requiring approximately 30 seconds to wick the length of a side wall.[5] For this calculation, the liquid drop is assumed to be at the far end of the groove relative to the waste filter.

The location of the tip of the wicking liquid filament has a height, d, of zero. If we define the tip location as $\mathcal{L}$ and set equation (3) equal to zero, the resulting expression is:

$$\pm\mathcal{L} = \frac{t^{0.4}}{C_2} \tag{4}$$

Note that the liquid is traveling in both the positive and negative directions; the origin being at the center of the drop. Examining C_2 (see Appendix D.2), it can be shown that the wicking distance of a liquid drop in a groove is proportional to $(\sigma t/\mu)^{2/5}$. The tip location, $\mathcal{L}$, as a function of time is illustrated on the inset plot of Figure 4.

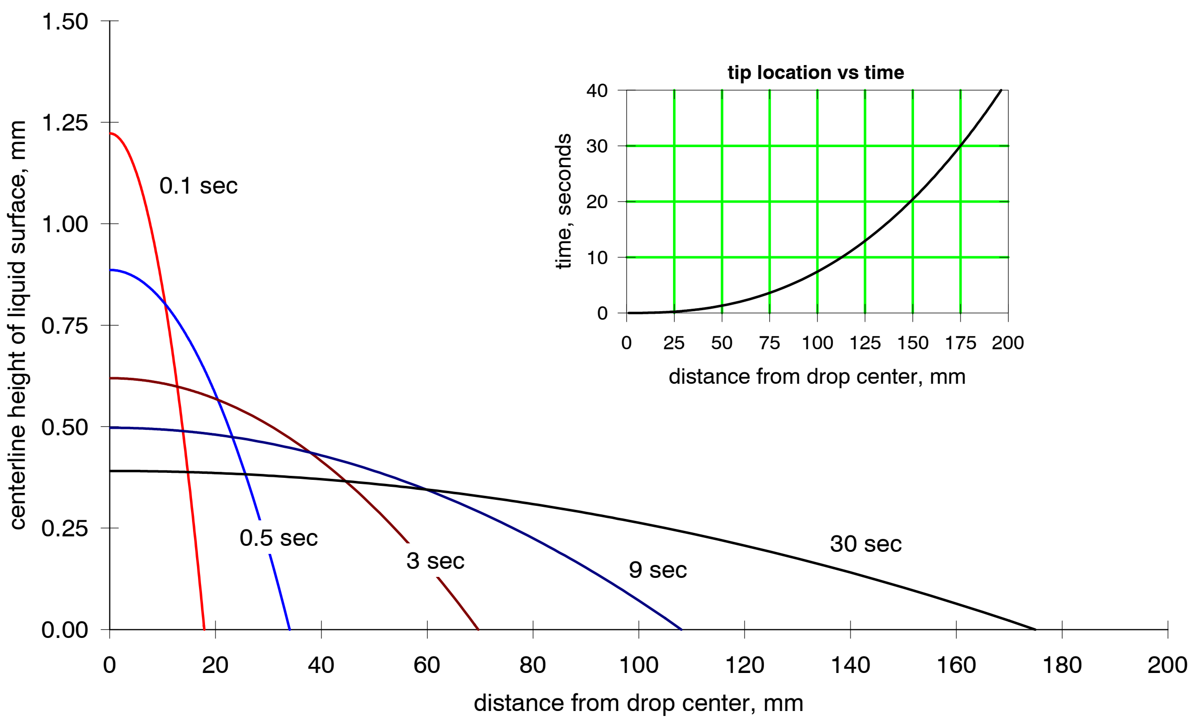

Figure 4: Plot of equation (3) for parameters listed in Table 4 for various times. The inset graph illustrates the tip location as a function of time as defined in equation (4).

The wicking rates illustrated in Figure 4 are significant and appear to be sufficient for getting the urine to contact the waste filter before significant evaporation occurs. The waste filter then must draw the liquid from the groove, again via capillarity. *Additional analysis is required to determine if the flow rate into the waste filter is sufficient to draw the majority of the liquid from the groove before urea crystallization begins.*

[5]The initial requirements for the volume of the Advanced Animal Habitat (AAH) resulted in a maximum wall length of approximately 20 cm. The side wall length estimates are described in §4.2.

4.1.2 Wicking with Debris in Groove

If a piece of debris, such as a food bar particle or hair, is in the groove then the wicking rate will be altered. For this scenario, the tip location is proportional to the square root of time

$$\mathcal{L}_2 \sim \left(\frac{\sigma}{\mu}\Psi t\right)^{1/2} \tag{5}$$

as opposed to equation (4). More importantly, the debris will act as a capillary trap; retaining a portion of the liquid at the debris location. The solids which deposit as the liquid evaporates will effectively plug that groove. Subsequently, liquid "upstream" of the debris relative to the waste filter will remain in the groove.

4.2 Liquid Retention

In addition to wicking liquid to the waste filter, the grooves also serve to capture and retain the waste fluids in order to "keep the animals as dry as possible". The purpose of this section is to determine the storage capacity of the four, parallel corrugated walls grooves should the waste filter not function properly because of a power failure or other unanticipated event.

4.2.1 Groove Geometry Constraints

The constraints on the groove geometry will be determined first. Then the grooves must be fit into the available volume. Finally, available volume can be calculated and compared to the expected urine production of the rodents for a specific period of time. Many of the constraints used for this section are defined by NCMR and may not reflect the actual design constraints required by the Principal Scientists; however, the design may be easily reevaluated with alternative design constraints.

The optimum groove half-angle for wicking was already determined in §4.1 to be 15°, but for convenience, we will use $\underline{\alpha = 14°}$. The depth of the groove, a, and the peak-to-peak distance, ℓ, (see Figure 3) must also be determined. We will require that ℓ be small enough that a typical rat feces will not enter the groove. Assuming that a typical rat feces may be approximated as a cylinder with a diameter of 2 mm, we will constrain $\ell \leq 2$ mm.

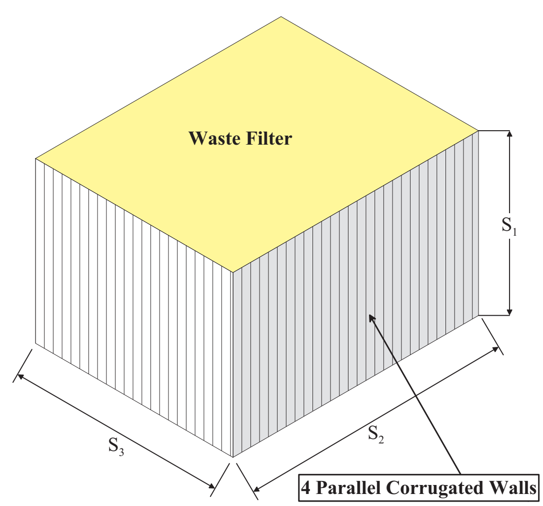

Figure 5: Definition of habitat dimensions S_1, S_2, and S_3.

The depth of the groove may be determined from α and ℓ as

$$a = \frac{\ell}{2 \tan \alpha} \tag{6}$$

which results in $a \approx 4$ mm. The cross-sectional area ($\frac{1}{2} a\ell$) defined by a groove with these dimensions is 4 mm^2.

4.2.2 Habitat Constraints

Now that the geometry of the groove has been specified, the length and number of grooves in the habitat will be calculated. The constraints on the habitat dimensions were provided to the NCMR as:

1. house six 400 gram rats with a minimum volume of 16,546 cm^3;
2. a minimum "height" (dimension S_1 in Figure 5) of 18 cm; and
3. a minimum "floor" diagonal ($\sqrt{S_2^2 + S_3^2}$) of 21 cm.

Most certainly, there are additional design constraints on the size and shape of the rodent habitat, but these constraints have not been provided to the NCMR. Therefore, we will specify the dimensions so as to meet the three constraints listed:

$$\left.\begin{array}{l} S_1 = 20 \text{ cm} \\ S_2 = 30 \text{ cm} \\ S_3 = 28 \text{ cm} \end{array}\right\rangle \begin{array}{l} \text{volume of 16,800 cm}^3\text{; exceeds minimum volume} \\ \text{"height" of 20 cm; exceeds minimum height} \\ \text{"floor" diagonal of 41 cm; exceeds minimum diagonal} \end{array}$$

4.2.3 Liquid Storage Capacity of Corrugated Liner

The volume of a groove with $\alpha = 14°$ and $\ell = 2$ mm with length $S_1 = 20$ cm is 0.8 cc (cc is an abbreviation for cubic centimeter). The number of grooves of which can fit in the dimension $2 \times (S_2 + S_3)$ is 580 which results in a total volume of 464 cc.

The lining and the waste filter of the Advanced Animal Habitat (AAH) will be periodically changed by an ISS crew member. Thus, the total volume required is dependent upon the number of days between change outs. The urine output of a 400 gram rat is 20 cc per day.[6] With six 400 gram rats, the urine output per day would be 120 cc. Thus the groove design only has approximately a 4 day capacity. Altering the design constraints for the groove, in particular ℓ, can dramatically change the storage capacity of the corrugated liner. Table 5 illustrates the effect of changing ℓ on the total volume while keeping α and S_1 fixed. Implicit in these calculations is the notion that there is a uniform distribution of liquid on the four, parallel corrugated walls. Also, the calculations do not account for drinking water which is released into the habitat by the rodents.

[6] Information provided by STAR in supplemental materials provided with original contract.

Table 5: Total volumetric capacity of corrugated liner with various values of ℓ for $\alpha = 14°$ and $S_1 = 20$ cm. S_2 and S_3 are kept nearly fixed at 30 cm and 28 cm, respectively. The CAPACITY IN DAYS column reflects the number of days required for six 400 gram rats to produce the volume in urine equal to the TOTAL VOLUME.

$\alpha = 14°$		$S_1 = 20$ cm		volume per	total #	TOTAL	CAPACITY
ℓ, mm	a, mm	S_2, cm	S_3, cm	grooves, cc	of grooves	VOLUME, cc	IN DAYS
2	4	30	28	0.8	580	464	~ 4
3	6	30	28.2	1.8	388	698.4	~ 6
5	10	30	28.5	5	234	1170	~ 10

4.3 Droplet Capture

4.3.1 Corner Radii

A liquid drop will tend to "pin" on any sharp edge. Liquid pinning is what allows a water glass to be overfilled without spilling. It is of particular concern when the static contact angle is greater than 30°. Therefore, if the peak of the grooves exposed to the rodents is sharp, a drop of urine may pin on a peak, not fully entering into the groove, and, thus, will not be wicked to the waste filter. Rounding the peaks, as shown in Figure 6, will help mitigate liquid pinning. The larger the radii of curvature, the less likely liquid pinning will occur. The limit is an infinite radii of curvature, i.e., a flat plate.

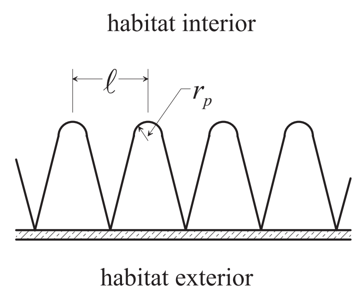

Figure 6: Radii of the peaks and valleys of the corrugations.

It is a complex design trade off between having a large radii of curvature (r_p), small peak-to-peak distances (ℓ), and good liquid storage capacity ($\frac{1}{2}a\ell S_1$). We recommend a peak radius of curvature of at least 0.5 mm; though this will still be a sharp corner when the static contact angle is 45°. Additional empirical data is required to further resolve the appropriate design parameters.

The valley of the grooves (relative to the rodents), conversely, should be as sharp as possible. This will allow for liquid to wick past debris, such as food bar particles and hair, thereby minimizing the chance of liquid holdup in a groove.

4.3.2 Material Selection and Surface Coatings

The capillary wicking of a liquid can be greatly affected by the choice of materials and/or surface treatments. Ideally, the groove surfaces should be as smooth as possible and the static contact angle should be as small as possible. The smaller the contact angle, the quicker a liquid drop will spread to the bottom (or valley) of the groove and the effects of contact angle hysteresis will be reduced.

A smooth surface will also minimize the effect of contact line hysteresis and accumulation of liquid films on the surface. For a *non-perfectly wetting system*, a drop of liquid will appear to spread better on a rough surface than on a smooth surface. However, when wicking in a groove, the rough surface will permanently capture a film of liquid which, for the AAH, can only be removed by evaporation. A semi-solid film will be deposited as the film of urine evaporates and the resulting surface will have a larger static contact angle than the pristine surface. Consequently, the propensity for contact angle hysteresis will increase and the rate of liquid flow in the groove will be reduced.

4.4 Unresolved Feasibility Issues

The corrugated liner concept relies upon liquid evaporation from the exterior surface of the waste filter for successful operation. The liquid feed from four of the habitat walls enters the waste filter through a series of point sources at the junction of the groove "valley" and the filter. At these junction points, debris and solid precipitates will accumulate, effectively plugging the waste filter to further liquid flow from the grooves. The rate at which the waste filter loses its permeability at the groove junctions needs to be determined.

The corrugated liner concept addresses liquid management on five of the six walls of the habitat; the four corrugated walls and the waste filter. The side of the habitat opposite the waste filter has not been evaluated relative to liquid management in a low-gravity environment.

4.5 Recommendations for Concept Verification

Figure 7 illustrates a potential feasibility study for the corrugated liner concept. A corrugated test plate is placed beneath a wire rodent cage at a slight inclination angle, ϕ. The length of the grooves is S_1 and the total rise of the plate is h. A capillary collector, or waste filter, is in contact with the upper end of the test plate. A gravity collector (tray) is placed at the lower end of the test plated. The purpose of this study would be to

1. qualitatively assess the effect of debris on liquid removal from the corrugated plate,
2. quantitatively assess the effectiveness of the grooves for moving liquid to the waste filter,
3. qualitatively assess the rate of liquid removal required in order to avoid precipitation of solids as the liquid evaporates.

All of the debris, urine and water from the rodent habitat will fall to the test plate. The grooves will tend to wick the liquid to a uniform thickness, d (see §4.1). If the concept is successful, the capillary collector at the upper end of the plate will draw the liquid out of the grooves. Little or no liquid will accumulate either in the grooves or fall to the gravity collector at the lower end of the corrugated plate. The inclination angle, ϕ, and the groove length, S_1, are parameters to be varied during the feasibility studies.

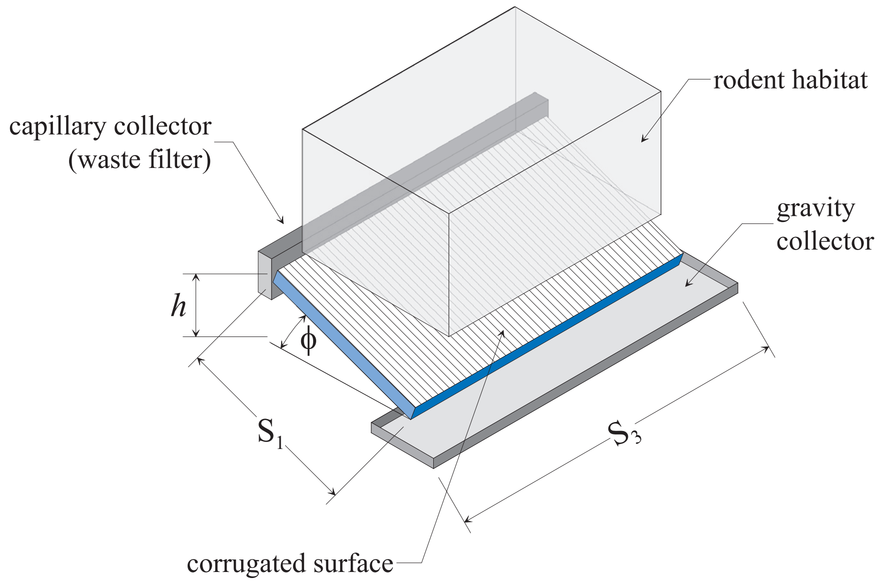

Figure 7: Illustration of feasibility study for the corrugated liner concept. The corrugated test plate is placed beneath a wire rodent cage at some inclination angle ϕ with a total rise of h. For a successful feasibility study, the capillary collector, or waste filter, should draw the liquid from the grooves without significant solid precipitation due to evaporation of the urine and without significant accumulation of urine in the gravity collector.

4.6 Summary of Evaluation of Corrugated Liner Concept

The corrugated liner concept has much promise. The wicking rates for fresh urine are substantial and the grooves can be designed such that a significant volume of liquid can be captured and retained; keeping the rodents suitably dry. However, several unresolved must be resolved:

1. As the urine evaporates, the fluid properties change dramatically with the potential to permanently block the grooves.

2. The liquid is wicked from the grooves into the waste filter at very small, fixed areas. There is the likelihood that the junctions between the grooves and the waste filter will quickly become impermeable which results in the grooves functioning solely as liquid accumulators.

3. The design of the wall opposite the waste filter for low-gravity liquid management has not been addressed.

4. The effect of debris on capillary wicking and overall liquid removal from the grooves needs to be studied.

5. The effect of contact line hysteresis and pinning prior to the liquid reaching the bottom of the groove needs to be studied.

6. Suitable materials for wicking and for establishing low static contact angles need to be investigated.

The feasibility study described in §4.5 would aid in resolving items 1, 2, and 4. Other types of tests would be required to resolve the remaining items.

5 Alternative Design Concepts

Alternative concepts for liquid management in the Advanced Animal Habitat are discussed in this section; though no detailed analysis of these concepts is provided. First, alternative wick structures are discussed for suitability in transporting urine. Second, the concept of transporting liquid normal to the habitat wall is discussed. Finally, these alternate wicking techniques are discussed in conjunction with a heat-pipe concept for removing the urine from the habitat.

The capillary wick structures are designed to develop high capillary pressure at the liquid-air interface, and must be optimized for maximum transverse capillary pumping. The properties of the wicks are:

1. minimum capillary radius
2. longitudinal and transverse permeability, and
3. contact angle.

Permeability is a measure of the wick resistance to transverse liquid flow. This parameter should be large in order to have a liquid drop pressure.

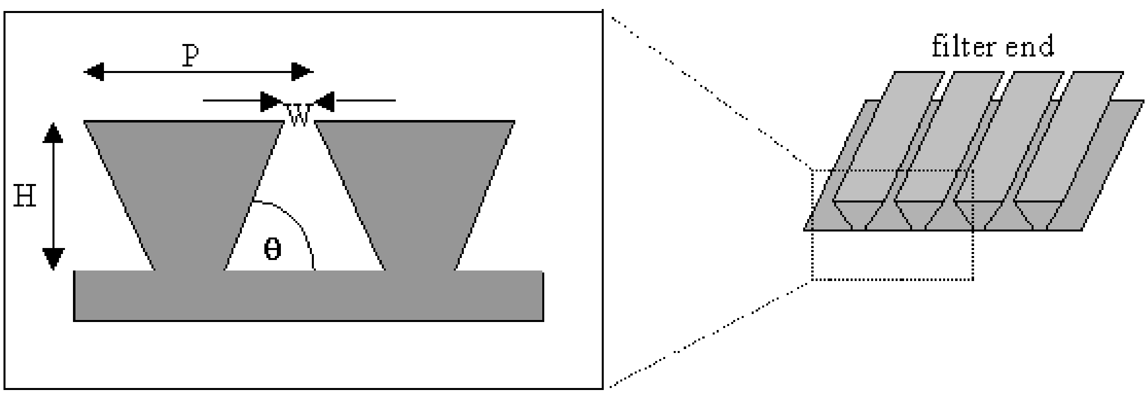

Figure 8: Trapezoidal wicking structures in which there are two effective grooves for transporting liquid in the transverse direction.

Two wick designs, a trapezoidal groove and "honeycomb" arrangement, are suggested. The first example shown in Figure 8 is a trapezoidal groove where the design parameters are H, P, W, and θ. H is the height of the wick, P is the periodicity, W is the effective capillary radius, and θ is the groove inclination to the horizontal. The trapezoidal groove structure would allow placement of a screen over the opening in order to increase the effective capillary radius. The advantage of the trapezoidal structure is that there are two effective grooves that can wick liquid in the transverse direction. The materials that may be used to construct these wick structures include, but are not limited to, sintered powders and foams, SiO_2 fibers, stainless steel, nickel, bronze, and titanium. However, titanium tends to be flammable in an oxygen-rich environment in microgravity. The surface treatment of a selected material is also important. Treatments such as glass bead and sand blasting tend to produce a low apparent contact angle, but caution should be exercised with surface treatments (see §4.3.2). A screen over the trapezoidal groove opening might allow one to initially prime the grooves with water and still allow for permeability of urine into the groove.

Another potential wicking structure is the honeycomb-like structure shown in Figure 9 where the "pores" may have a varying sectional diameter designed to maximize capillary driving potential in one direction. The shape of the inlets and outlets of the pores can be conical, triangular, hexagonal, etc. Any liquid that is not transported directly through the pores is captured in the region between pores and may be wicked in parallel to the habitat wall.

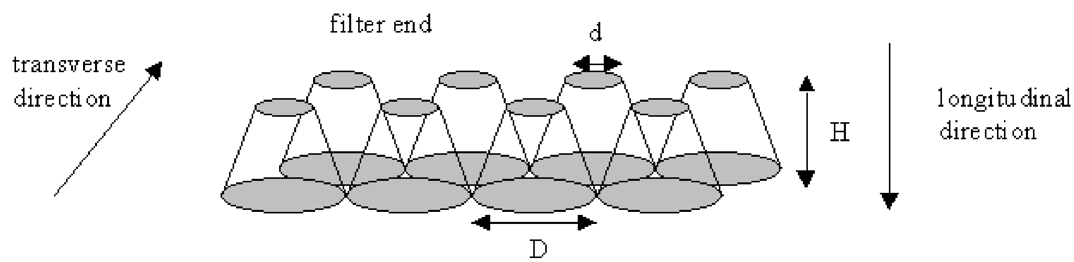

Figure 9: Example of a honeycomb-like wicking structures for transporting liquids normal to the habitat wall.

5.1 Heat Pipe Concept

The "heat pipe concept" is shown in Figure 10. A liquid-filled wick is in contact with a series of parallel cylinders which are separated by very small gaps. The parallel cylinders comprise the inner wall of the habitat. The gaps between the cylinders are sufficiently narrow such that the rodents can not reach the wick, yet are large enough that urine can be effectively transported normal to the cylinder axis into the liquid-filled wick. Heat is applied to the waste filter thereby evaporating water. The water vapor is transported between the outer containment wall and the wick via a slight pressure gradient due to the evaporative flux at the waste filter. The vapor recondenses on the wick and the liquid flows back to the waste filter to repeat the cycle. Similar systems, known as heat pipes or capillary-pumped loops, are commonly used for thermal control; using the latent heat of vaporization and the rapid flow of vapor for nearly isothermal heat transfer.

The adaptation of the heat pipe concept to a low-gravity rodent habitat allows for dilution of the urine for a potentially more efficient liquid transport to the waste filter. Evaporation of the urine and the subsequent solid precipitation would be confined to the waste filter which would be periodically replaced. The parallel cylinders comprising the inner wall allow for wicking parallel to the wall directly into the waste filter in a similar fashion to the corrugated wall concept. In addition, the heat pipe concept allows for transport of liquid normal to the interior wall into the liquid-filled wick. The osmotic pressure at between the urine and the

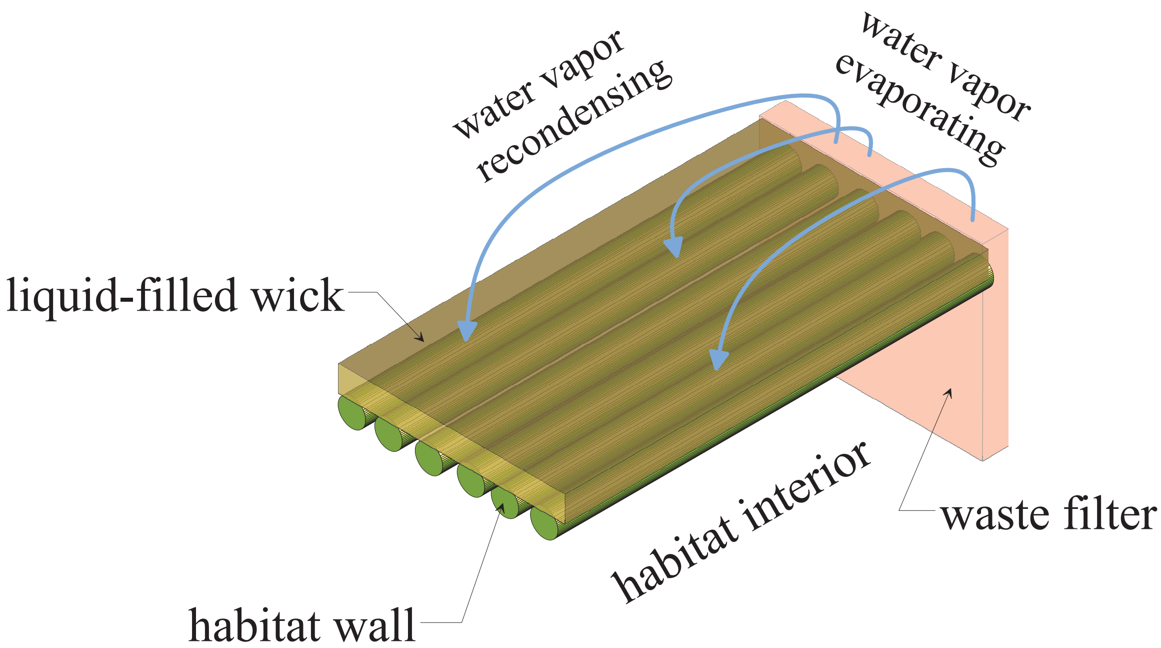

Figure 10: Cutaway illustration of the heat pipe concept showing the liquid-filled wick, parallel cylinders comprising the interior wall of the habitat, and the waste filter. Urine is transported via capillarity both normal to the habitat wall into the wick and parallel to the habitat wall into the waste filter. Water is evaporated from the waste filter and the vapor is recondensed on the wick. Liquid water flows towards the waste filter via capillarity and replenishes that which has evaporated. The water dilutes the urine so that all of the solids precipitate at the evaporation section of the waste filter.

water in the wick will draw the urine into the wick where it is transported with the water to the waste filter. In principle, the heat pipe concept for control of liquids in the Advanced Animal Habitat is nearly a self-sustaining system.

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B Statement of Work for Original Contract

November 14, 2000

Proposed Scope of Work

The National Center for Microgravity Research (NCMR) will render expert advice to STAR Enterprises, Inc. and Space Hardware Optimization Technology, Inc. (STAR-SHOT) in relation to the design of the Advanced Animal Habitat-Centrifuge (AAH-C) for NASA Ames Research Center which will house rats and mice on the International Space Station (ISS). Staff at the NCMR (Dr. John Kizito and Dr. Jeff Allen) shall consult on AAH-C fluid management in order to minimize specimen exposure to waste liquids and maximize subsystem performance across various ambient moisture levels. The proposed solutions should be effective for housing rats or mice during all parts of the AAH-C increment from launch to return under conditions ranging from microgravity to hypergravity when on the ISS Centrifuge Rotor.

The cooperative work between the NCMR and STAR-SHOT will be a phased approach with the initial focus on developing the overall concept of liquid waste management and a plan for verifying that concept in preparation for the Advanced Animal Habitat Preliminary Design Review. Inherent to any liquid waste management concept is the understanding that any structures, air flow, video/light ports, food and water delivery points within the specimen chamber have an effect on the ability to collect and move the liquid waste. Therefore, the NCMR and STAR-SHOT will have to work in close cooperation to insure the development of a successful design. The NCMR shall also measure the transport properties of the rodent urine so as to facilitate the design of the liquid waste management system.

Specifically, the initial phase of cooperative to between the NCMR and STAR-SHOT will include:

1. measuring the transport properties of rodent urine,
2. cooperatively developing a concept of managing fluids within the specimen chamber such that:
   (a) the animals remain suitably dry,
   (b) fluids within the specimen chamber are directed to the primary waste filter and/or liner for containment and/or evaporation,
   (c) fouling of the lighting subsystem, the camera lenses, and sensors within the specimen chamber is minimized,
   (d) liquid is deterred from entering air outlet, and
3. cooperatively developing a plan for concept verification. These three tasks are scheduled over a four months period.

STAR-SHOT will furnish appropriate biological samples from Rodent Food Bar-fed rats and mice. STAR-SHOT will conduct materials testing based upon the recommendations made by the NCMR unless otherwise agreed upon. The NCMR will provide an estimate of costs associated with conducting the research outlined in this scope of work.

Following the successful completion of the tasks listed above and the AAH-C Preliminary Design Review, the NCMR will continue to work with STAR-SHOT on additional tasks. The additional tasks include, but are not necessarily limited to:

1. prevent or remedy gas bubble formation in Water Delivery Subsystem, and
2. maintain bioisolation around the sealing surfaces of:
    (a) the inner housing walls and the food and water ports,
    (b) the sealing surfaces of the inner housing and top cover,
    (c) the sealing surfaces of the outer housing and top cover, and
    (d) the sealing surfaces of the outer housing front panel and the food delivery module (F) and front panel and the waste filter assembly (D).

At the appropriate time, a new scope of work, schedule and budget will be prepared.

Proposed Task Timeline

		Month			
	Project Task	1	2	3	4
1	**measurement of the transport properties of waste fluid;** see note below				
	a. density (3 temperatures, 3 concentrations)				
	b. viscosity (3 temperatures, 8 concentrations)				
	c. surface tension (3 temperatures, 3 concentrations)				
	d. contact angle (2 temperatures, 3 concentrations, 4 substrates)				
	e. pH (2 temperatures, 4 concentrations)				
	f. osmotic pressure (2 temperatures, 4 concentrations)				
	g. electrical conductivity (2 temperatures, 4 concentrations)				
2	**development of concept for managing fluids within the specimen chamber;**				
3	**development of verification plan for waste fluid management concept**				

Note: Measurement of the transport properties (task 1) will be made on both rat and mouse urine. The number of variations in temperature and concentration for each fluid is based on an estimate of the parameter range required in order to derive an accurate empirical constitutive model for the transport properties. Also, each measurement will have to be repeated at least three times to insure accuracy. It is anticipated that the density and surface tension variations with temperature and concentration will be roughly linear. The viscosity variation with temperature is anticipated to be linear, but the variation with concentration is anticipated to be nonlinear; the fluid is likely to become non-Newtonian as the concentration increases. The contact angle will be a function of the substrate as well as temperature and concentration and therefore the number of data points is subject to the types of materials selected for the specimen chamber. The pH, osmotic pressure, and electrical conductivity measurements will be conducted if and when necessary per the development of the waste fluid management concept. In summary, the total number of estimated measurements are:

density	27
viscosity	75
surface tension	27
contact angle	∼100
pH	24
osmotic pressure	24
electrical conductivity	24
estimated number of property measurements	∼ 301

Proposed NCMR Budget

The costs for NCMR's participation is divided into two categories. The first category is fixed expenses for equipment, supplies, travel, student support, etc. which are approximately $37k. The second category is scientist support. Because the NCMR and STAR-SHOT must cooperate as a team, it is not possible to determine the amount of time required by the NCMR science staff to support this project. Nominally, we estimate each staff member (John Kizito and Jeff Allen) will spend 25% of their time on this project. However, the exact amount of time required may be more or less during this period. In order to accurately reflect the science support, we are proposing to track and bill STAR-SHOT on a monthly basis for staff member time. The estimated cost for the four month period at 25% FTE for two staff scientists is $14k. The estimated cost for fixed expenses and monthly expenses for the four month period is $15k.

Other budget information of interest is that any equipment and/or supplies purchased by the NCMR through NASA incurs no overhead charges. And, currently, there is no depreciation charge for use of NASA equipment or facilities; this is subject to change without notice.

C Statement of Work for Contract Extension

Status of NCMR Contract with STAR/SHOT - May 28, 2001

NCMR was contracted to support STAR/SHOT in the development of the Advanced Animal Habitat (AAH) in the area of low-gravity fluids management. The following tasks were to be conducted over a 4 month period:

1. *measuring the transport properties of rodent urine,*
2. *cooperatively developing a concept of managing fluids within the specimen chamber such that:*
   (a) *the animals remain suitably dry,*
   (b) *fluids within the specimen chamber are directed to the primary waste filter and/or liner for containment and/or evaporation,*
   (c) *fouling of the lighting subsystem, the camera lenses, and sensors within the specimen chamber is minimized,*
   (d) *liquid is deterred from entering air outlet, and*
3. *cooperatively developing a plan for concept verification.*

To that end, NCMR has completed the following on each of the tasks:

Task 1 : NCMR has conducted most of the necessary property measurements. The details of the measurements taken as well as the data is included below.

Task 2 : NCMR has provided conceptual designs for the AAH and the SEU. A small workshop on low-gravity fluids management was conducted at SHOT on February 16, 2001. Various design concepts and the feasibility of those concepts for use in a low-gravity environment were discussed during several teleconferences and at the February 15-16 meetings.

Task 3 : To date there has been little communication on developing a plan for concept verification since the design concept has not yet been finalized.

During the 4 month contract period, NCMR has spent approximately $24k of the original $47k. The remaining $23k was intended to cover expenses relating to the hiring of a second undergraduate student, technician support, and feasibility experiments on liquid removal strategies. These activities were not conducted during the initial four month period because of time constraints and incomplete design criteria. NCMR anticipates an accelerated level of design evaluation now that the physical property measurements are nearly completed and STAR/SHOT has completed the initial PDR.

Proposed Continuation of NCMR Contract with STAR/SHOT

NCMR proposes to extend the original contract through August, 2001 in order to complete the three original tasks plus an additional task which is:

Task 4 : Support and participate in the Advanced Animal Habitat PDR scheduled to be conducted in August, 2001. NCMR will present the findings on the physical properties, the low-gravity fluids management concept, and the concepts for prevention of fouling of the lighting, video, and air exchange subsystems.

The $23k which remains from the original contract will likely suffice to carry this effort through June. In addition, there is currently sufficient travel funds allocated to NCMR personnel to participate for two days at the PDR. However, additional funding will be required to continue work up to and through the AAH PDR; particularly for PDR preparations. The anticipated schedule for completion of the four tasks is:

Task	June	July	Aug.	Comment
task 1. measurement of transport properties				additional measurements required as new biological samples delivered
task 2a,b. fluids management concept				NCMR to work with STAR/SHOT to refine details of design put forth at initial PDR
task 2c,d. minimization of subsystem fouling				NCMR to work with STAR/SHOT to conduct feasibility studies
task 3. plan for concept verification				NCMR to work with STAR/SHOT to provide detailed plan for design verification
task 4. support and participation in PDR				NCMR to present findings and details of low-gravity fluids management concepts

The proposed budget for continuing this work through the August PDR is as follows:

Direct	July		August	
Staff Scientist	(2) 0.25 FTE	$3,490	(2) 0.25 FTE	$3,490
Administrative	0.14 FTE	$850	0.14 FTE	$850
Undergraduate Student	(2) 1.0 FTE - 21 days	$5,105	(2) 1.0 FTE - 14 days	$3,403
Total Direct		**$9,445**		**$7,743**
Indirect		**$1,251**		**$1,026**
Total Direct+Indirect		**$10,696**		**$8,769**
			Total Proposed Augmentation to Current Budget	**$19,465**

The proposed budget augmentation is for 2 staff scientists at 25% time (Drs. Jeff Allen and John Kizito), administrative support, and for two full-time undergraduate students. The students would conduct additional physical property measurements and feasibility studies for various fluids handling concepts developed by STAR/SHOT and NCMR. The total budget augmentation would be $19,465.

Summary of Transport Property Measurements on Rat and Mouse Urine

The transport properties of rat and mouse urine were explored using various methods. The density of female rat urine was 1.002 g/mL, while the male rat urine averaged 0.967 g/mL. The average density of male mouse urine was 1.05 g/mL, while the female mouse urine was slightly less dense with an average of 1.03 g/mL. The average kinematic viscosity and surface tension of rat urine at 23°C were 0.9887 cSt and 36.47 dynes/cm, respectively. Both properties decreased with increasing temperature. The average kinematic viscosity and surface tension of mouse urine at 23°C were 1.122 cSt and 46.68 dynes/cm, respectively, and while the viscosity decreased with increasing temperature, the surface tension remained constant. The contact angles of rat and mouse urine on stainless steel were 45 and 47, respectively. On earth, hysteresis was a function of the volume of a droplet of urine. For very small volumes, there was no hysteresis when the substrate was rotated. When a Wilhelmy plate was immersed in a container of urine, the force measured exhibited hysteresis behavior at capillary numbers in the order of 10^{-4} (capillary numbers are the ratio of viscous to surface tension forces). The evaporation of mouse urine was linear at room temperature for the duration measured.

These results demonstrate that different strategies must be used for the removal of mouse urine in comparison to rat urine. Application of capillary transport techniques to the mouse urine must be performed as soon as the urine exits the animal. More studies will be needed to determine the relevant time scales, which describe the window of opportunity. The following table is a summary of the work done in fulfillment of task 1 outlined in the statement of work. A detailed report describing the above data will be submitted soon.

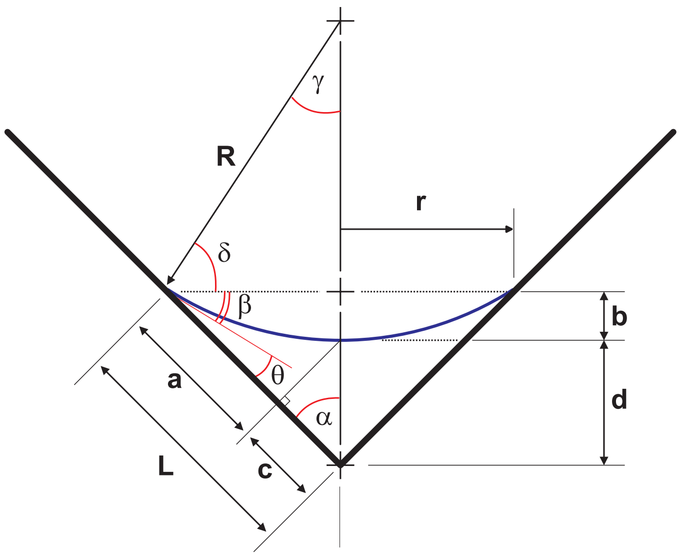
Task 1: Measuring the transport properties of rodent urine,

	rat	mouse	salt sol.	sucrose sol.	urea	ethanol	water	total
density	4	9	1	1			3	18
viscosity		16			50	24	28	118
surface tension	64	78	2	2	44			190
hysteresis	4	4						8
impact/spreading		1						1
contact angle	16	48						64
pH		9						9
osmotic pressure								0
electrical conductivity		4					4	8
evaporation rate		3				1		3
saturation point					1			1
							grand total	**420**

D Calculations

D.1 Groove Geometry Calculations

Figure 11 illustrates the geometry of a liquid surface in a low-Bond number wedge. The container could be very small with a radius of curvature of the liquid surface less than the capillary length[7] or the container could exist in a low-gravity environment. In either case, the surface is described by a spherical segment.



Important Parameters

α	$\equiv$	half-angle of wedge
θ	$\equiv$	static contact angle
R	$\equiv$	radius of curvature
L	$\equiv$	wetted wall length
d	$\equiv$	depth of liquid at centerline of wedge

Figure 11: Geometry of liquid surface in low-Bond number wedge. The liquid surface has a curvature of $1/R$ which is defined by the half-angle of the wedge, α, the equilibrium contact angle, θ, and the area of liquid in the cross-section, A.

From Figure 11, we can discern the following trigonometric relationships:

$$r = (d + b)\tan\alpha \tag{7}$$
$$r = L\sin\alpha \tag{8}$$
$$r = (R - b)\tan\gamma \tag{9}$$
$$r = R\sin\gamma \tag{10}$$
$$c = d\cos\alpha \tag{11}$$
$$b + d = L\cos\alpha \tag{12}$$
$$b = R\,(1 - \cos\gamma) \tag{13}$$
$$\beta = \pi/2 - (\theta + \alpha) \tag{14}$$
$$\gamma = \pi/2 - \delta \tag{15}$$
$$\beta + \delta = \pi/2 \tag{16}$$
$$L = a + c \tag{17}$$
$$L^2 = (d + b)^2 + r^2 \tag{18}$$
$$R^2 = (R - b)^2 + r^2 \tag{19}$$

[7] The capillary length is defined as $\sqrt{\sigma/\Delta\rho g}$, where σ is the surface tension of the liquid, $\Delta\rho$ is the density difference across the interface, and g is the gravitational acceleration.

D.1.1 Curvature Relationships

The aspect ratio of the liquid in the wedge, $r/(d+b)$, is defined by (7). However, the parameters r and b are difficult to measure. The parameters with which we would like to describe the system are the radius of curvature, R, the equilibrium contact angle, θ, the half-angle of the wedge, α, and the centerline depth of the liquid, d. Ideally, we would like to express R, d, cross-sectional area, A, and wetted length, L, only in terms of α and θ.

We can reduce the number of parameters used to describe the system by examining the above expressions. From (15) and (16), we find that

$$\gamma = \beta \tag{20}$$

In addition, the following can be shown to be true:

$$\begin{aligned} \sin\beta &= \cos(\alpha+\theta) && (21) \\ \cos\beta &= \sin(\alpha+\theta) && (22) \end{aligned}$$

Using (10), (13) and (20), we find that

$$\begin{aligned} \frac{r}{R} &= \sin(\beta) && (23) \\ \frac{r}{b} &= \frac{\cos(\beta)}{1-\sin(\beta)} && (24) \end{aligned}$$

Combining (7), (12), (21), and (23) results in a dimensionless expression relating meniscus curvature to wetted length of the wedge:

$$\boxed{\eta = \frac{R}{L} = \frac{\sin\alpha}{\sin\beta} = \frac{\sin\alpha}{\cos(\alpha+\theta)}} \tag{25}$$

Substituting (24) into (7) and rearranging gives

$$\frac{r}{d} = \frac{\tan\alpha}{1-\tan\alpha\left(\frac{1-\cos\beta}{\sin\beta}\right)} \tag{26}$$

Now, substituting (23) into (26),

$$\frac{R}{d} = \frac{\tan\alpha}{\sin\beta\left[1-\tan\alpha\left(\frac{1-\cos\beta}{\sin\beta}\right)\right]} \tag{27}$$

Equation (27) is complicated, but it can be simplified by expanding in terms of $\sin\alpha$.

$$\frac{R}{d} = \frac{\frac{\sin\alpha}{\cos\alpha\sin\beta}}{1-\frac{\sin\alpha(1-\cos\beta)}{\sin\beta\cos\alpha}} \tag{28}$$

Multiplying through by $\sin\beta\cos\alpha/\sin\beta\cos\alpha$ results in

$$\frac{R}{d} = \frac{\sin\alpha}{(\sin\beta\cos\alpha+\cos\beta\sin\alpha)-\sin\alpha} \tag{29}$$

Using the identity

$$\sin\beta\cos\alpha + \cos\beta\sin\alpha = \sin(\alpha+\beta) \tag{30}$$

and

$$\sin(\alpha+\beta) = \sin(\pi/2-\theta) = \cos(\theta) \tag{31}$$

we find that the term R/d can be expressed as a function of only α and θ. We define a new dimensionless curvature, Ψ, as

$$\boxed{\Psi = \frac{R}{d} = \frac{\sin\alpha}{\cos\theta - \sin\alpha}} \tag{32}$$

We can summarize the curvature relationships as follows:

$$\frac{r}{R} = \sin\beta \tag{33}$$

$$\frac{r}{d+b} = \tan\alpha \tag{34}$$

$$\Psi \equiv \frac{R}{d} = \frac{\sin\alpha}{\cos\theta - \sin\alpha} \tag{35}$$

$$\frac{r}{d} = \Psi\sin\beta \tag{36}$$

$$\frac{b}{R} = 1-\cos\beta \tag{37}$$

$$\eta \equiv \frac{R}{L} = \frac{\sin\alpha}{\sin\beta} = \frac{\sin\alpha}{\cos(\alpha+\beta)} \tag{38}$$

D.1.2 Area Relationships for Wedge Geometry

An expression for the cross-sectional area of liquid in the wedge may be derived in terms of R, α, and θ. The cross-sectional area of liquid is equal to the area of the wedge defined by base, r, and height, $b+d$, less the area of the spherical segment defined by base, r, and the radius, R. The two geometric areas are:

$$A_{wedge} = \frac{1}{2}(2r)(d+b) \tag{39}$$

$$A_{segment} = \frac{1}{2}R^2\Big(2\beta - \sin(2\beta)\Big) \tag{40}$$

Using the relationships (39) to (40), the cross-sectional area of liquid in the wedge can be expressed as:

$$A = A_{wedge} - A_{segment} = R^2\left[\left(\frac{r}{R}\right)^2\left(\frac{d+b}{r}\right) - \frac{1}{2}\Big(2\beta-\sin(2\beta)\Big)\right] \tag{41}$$

A dimensionless area is defined as $\boxed{\Lambda \equiv \frac{A}{d^2}}$. Substituting equations (33 – 35) into (41) produces:

$$\Lambda = \Psi^2\left[\frac{\sin^2\beta}{\tan\alpha} - \frac{1}{2}\Big(2\beta-\sin(2\beta)\Big)\right] \tag{42}$$

This expression may be rearranged as:

$$\boxed{\Lambda = \Psi^2 \left[\frac{\sin^2\beta + \cos^2\beta \tan\beta \tan\alpha}{\tan\alpha} - \beta \right]} \tag{43}$$

For a perfectly wetting system ($\theta = 0$), the term ($\tan\beta \tan\alpha$) is equal to 1 which reduces the bracketed expression in equation (43) to $(\tan\alpha)^{-1} - \beta$.

D.1.3 Perfectly Wetting Systems

For a perfectly wetting system, $\theta = 0$ degrees and the expressions described above may be simplified. Selected expressions can be shown to reduce to:

$$\eta \equiv \frac{R}{L} = \tan\alpha \tag{44}$$

$$\Psi \equiv \frac{R}{d} = \frac{\sin\alpha}{1 - \sin\alpha} \tag{45}$$

$$\Lambda \equiv \frac{A}{d^2} = \Psi^2 \left(\frac{1}{\tan\alpha} - \frac{\pi}{2} + \alpha \right) \tag{46}$$

Using the preceding relationships, the radius of curvature of a surface, R, can be determined from the wedge angle, the contact angle, and liquid volume or depth. Conversely, a specific radius of curvature can be obtained by properly specifying the liquid volume and the wedge angle.

D.2 Capillary Wicking Calculations

The solution of the centerline height, d, as a function of groove location, z, and time, t, was derived by Weislogel [1-3] using a constant volume constraint. In this analysis, the constant volume, V, is that of a single drop off rat urine. The following is a summary of the derivation found in references 1 and 2, but the nomenclature has been changed for consistency in this report. The geometry is described in Figure 3.

D.2.1 Capillary Wicking of a Drop in a Corner

The centerline height of a spreading drop in an infinite corner yields to a similarity solution of the form

$$d(z,t) = \frac{C_1}{t^{0.2}} \left[1 - \left(\frac{C_2\, z}{t^{0.4}} \right)^2 \right] \quad , \tag{47}$$

where

$$C_1 = \left(\frac{45V^2}{256\Lambda^2 G}\right)^{1/5} \text{; units of m/sec}^{1/5} \tag{48}$$

and

$$C_2 = \left(\frac{16\Lambda}{375G^2 V}\right)^{1/5} \text{; units of sec}^{2/5}\text{/m} \tag{49}$$

where Λ and G are functions and V is the drop volume.

The dimensionless area, Λ, was derived earlier (see equation (43) in Appendix D.1) and is equal to the cross-sectional area, A, divided by the square of the meniscus height, d. Λ is constant with respect to z even though d is a strong function of position! The function G is defined as:

$$G = \frac{\sigma F_i \sin^2\alpha}{\mu\Lambda} \tag{50}$$

where $1/8 < F_i < 1/6$. For the case where $\alpha = 15°$ and $\theta = 45°$, equation (50) can be simplified to the following form:

$$G = \frac{\sigma\Psi}{10\mu b} \tag{51}$$

where $3 < b < 4$.[8] Recall that Ψ is the aspect ratio, R/d, where R is the radius of curvature of the meniscus (see equation (32) in Appendix D.1). Therefore, the function G may be described as a capillary velocity scaled by the wedge geometry.

If equation 47 is set equal to zero and solved for z, the tip location as a function of time is found to be:

$$\mathcal{L} = \frac{t^{2/5}}{C_2} \tag{52}$$

which, when expanded becomes:

$$\mathcal{L} = t^{2/5}\left(\frac{375G^2V}{16\Lambda}\right)^{1/5} \tag{53}$$

This expression can be simplified by recognizing that the key parameters are captured by the capillary velocity scale, G, and that the remaining terms are constant. Therefore,

$$\mathcal{L} = \left(\frac{\sigma}{\mu}\Psi t\right)^{2/5}\left\{\frac{375V}{16\Lambda}\left(\frac{1}{10b}\right)^2\right\}^{1/5} \tag{54}$$

The last, bracketed term of equation (54) is constant. So the tip location is found to be proportional to

$$\mathcal{L} \sim \left(\frac{\sigma}{\mu}\Psi t\right)^{2/5} \tag{55}$$

[8] **Caution:** This range of values for b is only valid for $\alpha = 15°$ and $\theta = 45°$ and is used here to illustrate the physical significance of G. Calculations for other values of α and θ should use equation (50) and $1/8 < F_i < 1/6$.

D.2.2 Capillary Wicking with Debris

If a piece of debris is in a groove with liquid, then the debris will act as a capillary trap retaining a portion of the liquid and altering the wicking rate. Weislogel [2] also derived the solution for this condition (constant height constraint). For this case, the tip location is proportional to the square root of time:

$$\mathcal{L}_2 \sim \left(\frac{\sigma}{\mu}\Psi t\right)^{1/2} \tag{56}$$

D.2.3 Optimum Wicking Angle

The maximum rate of capillary wicking in a groove may be found by maximizing the value of the spreading coefficient, K:[9]

$$K = \frac{1}{\Lambda^{1/5}}\left[\frac{\sin^2\alpha}{\Psi}\right]^{2/5} \quad ; \tag{57}$$

where

$$\Psi = \frac{\sin\alpha}{\cos\theta - \sin\alpha} \quad , \tag{58}$$

$$\Lambda = \frac{\Psi^2\sin^2\gamma}{\tan\alpha}\left[1 - \left(\frac{2\gamma - \sin^2\gamma}{1-\cos 2\gamma}\right)\tan\alpha\right] \quad \text{, and} \tag{59}$$

$$\gamma = \frac{\pi}{2} - (\alpha + \theta) \tag{60}$$

The relationships described above are geometric in nature[10]; that is, the fluid properties do not enter into the expressions except through the static contact angle. The values of the spreading coefficient, K, for $\theta = 45°$ and various values of α are listed in Table 3; where the maximum value of K occurs when $\alpha = 15°$.

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[9] see Weislogel & Lichter (1996) "A Spreading Drop in an Interior Corner: Theory and Experiment", *Microgravity Science and Technology*, **IX**/3, 175–184. Additional information may be found in the bibliography listed in Appendix A.

[10] Equations (58), (59), and (60) are equivalent to equations (32), (43), and (14), respectfully, the latter which are derived in Appendix D.1.

E Physical Property Measurements

E.1 Physical Measurements of Rodent Urine

This report describes (*i*) the urine samples tested and the collection techniques, (*ii*) the measurement techniques for determining the density, viscosity, surface tension, contact angle hysteresis, contact angle, and evaporation rate, and (*iii*) the results of those measurements for mouse and rat urine.

Link to Report

E.2 Effect of Surface Treatment on Static Contact Angle

This report describes the effect of surface roughness and material selection on the static contact angle. The measurement techniques, data analysis and results are presented for both male rat urine and water at room temperature.

Link to Report