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The Cost and Equivalent System Mass of Space Crew Time

Harry W. Jones
NASA Ames Research Center

ABSTRACT

In “Theory and Application of the Equivalent System Mass Metric,” Levri, Vaccari, and Drysdale computed the Equivalent System Mass (ESM) of crew time. ESM is a cost-type metric based on allocated mass that is often used in life support systems. The previous paper suggested that the cost per hour of crew time should be equal to the ESM of the life support system, divided by the number of available crew work hours. We suggest here that the mass cost for additional crew time may be as large as the total mission mass or as small as the added mass of consumables, depending on how much more crew time is needed. If the increased mission work load requires flying additional crewmembers, the total mass and cost of the mission increases roughly proportionally to crew size. But if the needed work can be done merely by extending the mission duration, the required additional mass is only that of the food and supplies to be consumed during the time extension. The resulting upper and lower bounds on cost per hour of crew time are within an order of magnitude and can help resolve design decisions even when the total demand for crew time is unknown. However, the cost of crew time used in mission planning should not always be the actual cost to provide that time. The cost should be set at a level that ensures that the crew is neither under or overloaded. If little work is needed, we should set the price of crew time low or at zero to encourage more tasks. If the crew time demand is excessive, the cost should be set high to reduce the task requests. Imposing a low cost for low total demand and high for high will help guide the sum of crew time requests to converge to the desired workload.

INTRODUCTION

We discuss the use of Equivalent System Mass (ESM) or allocated cost in systems evaluation and describe how to compute them. Cost and ESM are single numbers and the detailed information used to compute them is often needed to compare systems. ESM does not usually include crew time although crew time may have significant impact on systems choices. We describe the method for computing the ESM of crew time previously proposed by Julie Levri, David Vaccari, and Alan Drysdale. We then present a calculation of ESM made by John Hogan which computes the ESM of crew time using this method. The ESM for a small amount of crew time seems high. We then investigate the mass and ESM that is required to provide additional crew time. This actual cost is less than the increase in the entire system mass needed to fly an additional crewmember but more than the food and consumables required to extend the mission duration. The difference between these maximum and minimum costs is less than an order of magnitude, so cost-based design decisions involving very large or small amounts of crew time can be made without a closer determination of cost. Space missions vary in expected workload and crew time may not always be a scarce resource. Both under and over use of the crew are serious problems, and we can use the assigned cost of crew time to optimize workload. Regardless of the actual high cost, we would want to provide crew time free of charge if the crew was in need of meaningful work, as is possible during a transit to Mars. We show how we can regulate the use of crew time by setting a high cost initially, assuming crew time is scarce, and then reducing cost as low as zero, if we find crew time is underutilized. Setting a charge for crew time should lead to more efficient allocation than simply allocating crew time to users.

COST, MASS, AND ESM

The simplest way to evaluate different space missions or to compare different designs for the same mission is to compare their estimated costs. Mass is a major cost factor for aerospace systems. The cost to launch mass to orbit is significant. Mass is often used to estimate the cost for design and development of aerospace equipment. "Typical relationships used to estimate the cost of a spacecraft's hardware rely on weight as the driving characteristic." (1) Whether we are evaluating the choice between a human Moon or Mars mission or comparing two Mars scenarios, we can use the total mission mass to roughly estimate cost.

The mass is also a good way to compare alternate designs for particular systems such as life support, as the mission mass is always strictly budgeted. Other cost factors including volume and power must also be considered. The total cost for a particular system can be minimized if the mission and the systems architecture are known. This is more difficult when the next crewed space mission is undefined. We need to evaluate different systems designs and to select the best subsystem technologies for research even though the mission and the systems constraints are uncertain.

Equivalent System Mass (ESM) is often used in life support systems analysis to combine the costs of system mass, volume, power, and cooling in a single mass number. ESM provides a single figure of merit to compare the costs of different system design approaches or different subsystem technologies.

COMPUTING ESM AND COST

ESM is easily computed from the actual mass, volume, power, and cooling needs of a system. First, we sum the launch weights of all the equipment of the system. Next, we compute the equivalent mass factor for the system volume. This is usually done in two steps. Given a structure with known mass and volume, we divide the mass by the volume to determine the equivalent mass per unit volume. Multiplying this equivalent mass per volume by the volume of our system, we obtain the equivalent mass of the particular system's volume. The ESM including mass and volume is the actual system mass plus the mass of the structure needed for the system. The mass equivalent of the system power is found similarly. The power supply requires a certain launch mass and volume. The power supply ESM based on its mass and volume is divided the power supply capacity to determine the equivalent mass per kilowatt. Multiplying this equivalent mass per kilowatt by the system power requirement, we obtain the equivalent mass needed to provide power for the particular system. The ESM including mass, volume, and power is the mass of the system, plus the mass of the structure it needs, plus the mass of the power supply it needs. ESM also includes the allocated equivalent mass of the thermal cooling system, found similarly. The ESM depends on the type of structure, power supply, and cooling system used on the mission, and these determine the mass equivalents of volume, power, and cooling. (2)

The major reason to use ESM is to compare different systems designs and technologies for different mission scenarios or different systems architectures. A particular system’s mass, volume, power, cooling, and crew time may remain the same for all missions for a given crew size, but the mass equivalents usually change with the mission and design approach, since these affect the structure, power supply, and cooling technologies.

Cost is a more usual metric than ESM in aerospace, except in life support. The basic system cost is found similarly to ESM. The cost of a system is the cost of its hardware, plus the cost of its system volume, plus the cost of the power supply, plus the cost of the cooling. ESM is an analog of cost. It was originally introduced in life support analysis to avoid dealing with the large dollar figures typical in human space exploration and to avoid the further complexities of cost estimation and time value discounting.

Cost and ESM reflect differences in costs but not in benefits. We build systems for their performance, including safety, reliability, and usability. Comparing systems by cost alone implies they provide identical performance. Choosing for minimum cost or ESM is a good way to select between systems that have been designed to meet the same requirements, but minimizing cost or ESM is not always the best way to design systems. ESM or cost is only one number, a single valued metric. To help guide design choices, we should consider the mass, volume, power, and cooling requirements along with total ESM or cost. ESM usually does not include crew time. (2) Analyzing the ESM or cost of crew time is the purpose of this paper.

INCLUDING CREW TIME IN COST AND ESM

Just as different life support system designs use different mass, volume, power, and cooling, they require different amounts of crew time for operation and maintenance. Crew time is an additional cost factor. It would be useful to include crew time in the top-level system comparisons and technology selections using cost or ESM. Increasing the crew size requires adding habitat and life support, while saving crew time requires flying labor saving equipment. Since providing more crew time requires additional mass, volume, power, and cooling, crew time has a computable ESM and cost.

In a previous paper, “Theory and Application of the Equivalent System Mass Metric,” Julie Levri, David Vaccari, and Alan Drysdale (3) developed a method for computing the ESM of crew time. We give a simplified explanation of that method. They first compute the ESM of the entire life support system based on mass, volume, power, and cooling, here designated ESM (m, v, p, c). They then divide ESM (m, v, p, c) by the number of crew work hours per crew member per week, which gives the mass equivalent of crew time. This mass equivalent is applied to time spent on life support operations and maintenance to compute the cost of crew time, ESM (ct). The calculation of equivalent mass including crew time, ESM (m, v, p, c, ct), is as follows:

ESM (ct) = [ESM (m, v, p, c)/crew hours]*
[operations hours spent]

ESM (m, v, p, c, ct) = ESM (m, v, p, c) + ESM (ct)

The justification for applying this cost is that the limited available crew time is over-requested and that any the crew time not spent on the main mission objective should be penalized. Time spent on operations and maintenance should be replaced by increasing the crew size and the life support system, or at least charged for at this replacement rate to limit the demand for crew time.

The current paper suggests several changes to the original approach for computing the cost of crew time. First, the actual cost of crew time may be more or less than the ESM of the life support system, depending on the amount of crew time needed. Second, on some missions the crew time needed may be less than the hours available, and then it is not appropriate to charge the actual cost. The crew needs important interesting work. Third, the objective of assigning a cost to crew time should be to ensure the best use of the available time, and encourage the appropriate use of labor saving equipment in both mission science and crew support. We should not necessarily minimize the total use of crew time or direct it from crew support to science. These points are discussed below. We first consider an example calculation of ESM including crew time using the method originated by Levri, Vaccari, and Drysdale.

CALCULATION OF REACTOR ESM WITH CREW TIME

John Hogan, Sukwon Kang, Jim Cavazzoni, Julie Levri, and Cory Finn compared continuous and batch composting reactor systems using ESM including crew time for a Mars base. (4) John Hogan later provided the data for this analysis, shown in table 1 below. (5) The mass equivalents for volume, power, and cooling are for the Mars surface and are from table 1 of Levri, Vaccari, and Drysdale.

Table 1: Batch and continuous reactor ESM.

	Parameter	Batch	Continuous	Mass equivalent
1	Reactor dry mass (kg)	255	95	
2	Compost mass (kg)	215	236	
3	Associated equipment (kg)	90	40	
4	Total mass (kg)	560	371	
5	Reactor volume (m^3)	4.2	1.3	
6	Storage requirements (m^3)	0	0.5	
7	Total volume (m^3)	4.2	1.8	2.08 kg/m^3
8	ESM (v)	8.7	3.7	
9	ESM (m, v)	569	375	
10	Power (kW)	0.72	0.645	86.9 kg/kW
11	Cooling (kW)	6.5	1.15	66.7 kg/kW
12	ESM (p, c)	496	133	
13	ESM (m, v, p, c)	1065	507	
14	Crew time (hours/person-week)	1/4	1/3	5,010 kg/h/pers.-wk
15	ESM (ct)	1,253	1,670	
16	ESM (m, v, p, c, ct)	2,318	2,177	

The computations of table 1 follow the ESM procedure described above. The masses of the two systems to be compared are given in rows 1 through 3 and are totaled in row 4. The continuous bioreactor has only two-thirds the mass of the batch system. Volumes are given in rows 5 and 6 and are totaled in row 7, where the mass equivalent of volume is also given. The ESM of the volume is given in row 8 and the total ESM for mass and volume in row 9. The volume ESM is insignificant. The power and cooling loads are in rows 10 and 11, with the mass conversion factors from table 1 of Levri Vaccari, and Drysdale (3). The ESM for power and cooling is significant, as shown in row 12. Row 13 shows that the ESM considering mass, volume, power, and cooling is twice as high for the batch reactor as for the continuous reactor. Row 14 shows that the batch reactor requires 1/4 hour, or 15 minutes per crew member per week, while the continuous reactor requires 1/3 hour, or 20 minutes per crew member per week. The crew time mass conversion factor of 5,010 kg per hour per crew member per week in row 14 was calculated by the method of Levri, Vaccari, and Drysdale based on the ESM of the life support system. The resulting ESM of crew time in row 15 dominates the total ESM in row 16.

If the choice between the batch and continuous reactor was made on the basis of actual mass (batch 560 kg, continuous 371 kg), or on the basis of ESM (m, v, p, c) (batch 1065 kg, continuous 507 kg), the continuous reactor would be selected. But adding the ESM of crew time based on the ESM of the life support system makes a significant difference. If the choice between a batch and continuous reactor was based on the ESM (m, v, p, c, ct) (batch 2,318 kg, continuous 2,177 kg), it would be too close to call.

The assumptions and method used to compute the ESM of crew time are reasonable, but the result is unexpectedly weighty. The difference in crew time needed for the batch and continuous reactors is only five minutes per crewmember per week. The ESM for this five minutes of crew time per crewmember per week is 418 kg, roughly equal to the actual masses of the reactors. But five minutes per week is much smaller than typical scheduling uncertainties. Would we really fly a system with ESM (m, v, p, c) of 1065 kg rather than 507 kg just to save five minutes per crewmember per week? The result seems questionable. Is the ESM for five minutes of crew time too high? We will take a closer look at computing the mass equivalent of crew time.

LIFE SUPPORT ESM AS THE COST OF CREW TIME

The mass equivalent of crew time is the ESM cost assigned to all the crew time divided by the number of crew work hours per crewmember per week. The calculation of the mass equivalent of crew time made by Hogan *et al*. for table 1 above and two examples using data from Levri, Vaccari, and Drysdale (3) are shown in table 2 below.

Table 2: Mass equivalents of crew time.

	Example	ESM cost of all crew time (kg)	Crew time (h/pers.-wk)	Mass equivalent of crew time (kg/h/pers.-wk)
1	reactors of table 1 above	311,100	62.1	5,010
2	International Space Station	211,257	56.1	3,765
3	Mars combo lander	66,947	62.1	1,078

In all cases in table 2, the cost of all the crew work time is the ESM (m, v, p, c) of the life support system. The first row gives the mass equivalent of crew time used in the reactor example of table 1 above for a Mars base scenario. The second row from Levri *et al*. table 2 (3) gives the life support ESM and crewmember workweek for the International Space Station reference mission and the resulting mass equivalent of crew time. The third row from Levri *et al*. (3) uses the life support ESM and workweek for a Mars combo lander. The ESM of crew time for the Mars combo lander is significantly lower.

The mass equivalent of crew time is the assigned ESM (here the life support system ESM) divided by the crew time per person per week. The crew hours per person per week has a known limited range, which we can assume to be 60 ± 20 hours. The ESM penalty assigned to all the crew time varies more widely, five to one in table 2. The major cause of the variation in the ESM penalty is the difference in life support ESM, which depends on the mission and design approach. We next consider alternate bases for the cost of crew time.

MISSION OR CONSUMABLES MASS AS THE COST OF CREW TIME

Is the correct cost of crew time equal to the ESM of the life support system? What mission mass is actually incurred to provide the crew work time? Is it the life support ESM, or the crew habitat ESM, or the entire mission mass? Or is the cost only the consumables needed to support the crew?

Most of the mass of a human space mission is needed to transport and support the crew, so the total mass and cost are approximately proportional to the number of crew (ignoring economies of scale). If we assume that the main purpose of the mission is to provide crew time, the total system mass is the appropriate cost for all the crew time. Since we can fly additional crew members at this cost, it is the actual upper bound on crew time cost.

Since much of the mass of a human space mission is needed for a stay of any duration, the total ESM and cost do not increase proportionally to mission duration and crew labor supplied. But if we extend the mission duration, we must at least supply the daily consumables. The incremental cost for extended duration defines a lower bound on crew time cost.

Table 3 below shows three different mass equivalents of crew time for a Mars mission, based on full surface mass, life support mass, or consumables mass. These values are based on a recently published study. (6, 7)

Table 3: Mars surface mission mass equivalents of crew time.

	Example	ESM cost of all crew time (kg)	Crew time (h/pers.-wk)	Mass equivalent of crew time (kg/h/pers.-wk)
1	full surface habitat lander mass	61,034	60.0	1,017
2	life support mass	20,600	60.0	343
3	consumables mass	10,200	60.0	170

The total mass of a Mars habitat lander for six crew and 680 days is 61,034 kg. The life support system ESM for 680 days is roughly 20,600 kg. ESM was computed using the Mars surface mass equivalents in table 1 above, taken from table 1 of Levri *et al*. (3) This 20,600 kg is about one-third the life support ESM of the combo lander in table 2. The consumables are only 10,200 kg, 9,400 kg of hydrated food and 800 kg of cleaning supplies. Assuming 60 hours per crewmember per week, the mass equivalents are roughly 1,000 kg, 350 kg, and 170 kg per hour per crewmember per week.

We have bounded the ESM of crew time. The assigned ESM penalty of crew time should be less than the total mission mass and greater than the consumables mass. The total mass is the actual maximum cost to provide more crew time, while the consumables mass is the actual minimum mass.

It seems that the ESM of the life support system is a reasonable rough estimate of the cost of all crew time. The assigned ESM cost of crew time should be less than the total mission mass, which is three times the life support ESM. The assigned cost should greater than the consumables mass, which is half the life support ESM. The habitat mass/life support ESM/consumable mass ratios are roughly 6/2/1.

The upper bound on the cost of crew time derived from the total mission mass is within an order of magnitude of the lower bound derived from the consumables mass. Using either of these values, or the intermediate life support system mass, would provide the accuracy usually expected in ESM computations. "Another word of caution about the equivalent-mass concept - it provides only a rough order-of-magnitude calculation for comparing LSS configurations in the very early stages of mission planning. We must consider many other issues when moving to the next phase of actual system design." (2)

If the difference in crew time between two design approaches is very small or very large, we can use the upper and lower cost bounds to make definite design selections. Consider the example of table 1. If we use the habitat lander mass equivalent of crew time in table 3 above to determine the cost of crew time, the ESM for the difference of five minutes per crewmember per week in table 1 is 1,017/12 = 85 kg. This is the maximum crew time ESM that could be charged to the continuous reactor for using 5 minutes more crew time. Since the continuous reactor has 190 kg lower mass and 550 kg lower ESM than the batch reactor, we can choose the continuous reactor even though it uses more crew time.

If the much higher mass equivalent of crew time in table 1 is used, the choice of reactors will change depending on whether the upper or lower bound mass cost is assigned to crew time. In table 1 the choice still marginally favors the continuous reactor. But the cost of crew time in table 1 is based only on the life support system mass. If we used all the surface mass we would have a three times higher cost for crew time. In this case the five minutes difference would be charged 1,250 kg and the batch reactor would be chosen.

Because the required crew time is so little, we should use only the ESM of the consumables as the cost of crew time for this reactor example. If we choose the continuous reactor, the crew time increases 5 minutes per crewmember per week. For six crew and 680 days, this is a total of 48 hours work. With six crew each working 60 hours per week, the mission must be extended only one day. Only the consumables mass will increase. We can pick the continuous reactor even though it requires slightly more crew time.

IS THE CORRRECT COST ALL THE MASS OR ONLY THE CONSUMABLE MASS?

We now have the actual upper and lower bounds on the cost of providing crew time. Which should we use when? Let's reconsider the reactor example from an overall mission point of view. A well planned mission will have a reasonable crew work load. An additional five minutes per crewmember per week should be no problem. If we originally picked the batch reactor based on the high cost of crew time corresponding to all surface mass, we would change to the continuous reactor to save mass. The maximum mass increase is the consumables for one day, but we might instead decide to cut back other work.

The obvious problem with this reactor example is that we propose to charge only the small actual additional cost of the added crew time. There is no doubt that this is the real cost that affects the decision. All else being equal, we can actually supply the required time by extending the mission and increasing the consumables. But what about the total cost to provide the crew in the first place? An analogous case might be a planned ten day trip to Europe. Airfare is $1,000 and hotel is $100 per night, a total of $2,000 or $200 per day. But we can extend the trip for $100 per day, the hotel cost alone. The cost of airfare does not affect the decision to extend or not, even if it was $10 or $100,000. On the other hand, the airfare cost does affect the choice to take a second trip. And the large actual cost of increasing crew size on Mars is the full surface mass.

The appropriate cost for crew time depends on the amount of crew time we are considering. If the required crew time is small, we should use only the ESM of the consumables as the cost of crew time. If the required crew time is large, we should use the entire surface mass as the cost of crew time.

If the available crew time is heavily over-requested, the users of crew time should be assessed the full cost of adding more time. But if there is low total demand, the users of crew time will not pay enough to cover the real out-of-pocket cost of the currently obtainable time. Is it possible that the crew could have more time available than is needed for work?

SPACE CREW TIME MAY NOT BE OVERSUBSCRIBED

A mission plan may provide more crew time than can be usefully applied. In life support ground tests there is typically low demand for crew time. Crew time in the McDonnell Douglas 90 day test was definitely underutilized. The time actually spent was 8.8 hours per day per crewmember for sleep, 8.9 free time, 3.4 on operations tasks, 2.1 eating and cleanup, and 0.8 unaccounted. Unplanned operations work varied from 0 to more than 4 hours per day per crew member, with an average of 1.3 hours. The crew often responded to new unscheduled task requirements by reducing the time spent on scheduled tasks such as meals and exercise rather than reducing free time. “The crew reported its primary difficulty resulting in boredom was the inadequacy of the work program. ... As with most group confinement studies, inactivity or free time not devoted to productive mission-related work may be considered anathema and the primary problem to overcome in successfully scheduling activities of crewmen for long duration confinement situations.” (8) Work expands to fill the time available. People in ground tests spend their time watching plants grow or taking apart and reassembling clunky molecular sieves. Excess crew time should be employed at no charge, regardless of the initial cost incurred to provide the crew time.

Space missions vary in expected work load. As Levri, Vaccari, and Drysdale observed, crew time might not be a limited resource during transit to and from Mars. Clearly the purpose of the journey is not for the crew to work in transit. The International Space Station crew loading plan anticipates high demand for crew time. The specified crew work time is restricted to 8 hours per crewmember for five days each week. Other planned crew work day activities are 2 hours per day for exercise, 3.5 for meals, 8.5 for sleep, 1.5 personal time, and 0.5 for ground coordination and planning. Such strict guidelines prevent overloading the crew. But in addition, 80 crew minutes per day will be available for payloads operations during off-duty days and days when utilization time is otherwise unavailable, and 4 hours per crewmember of station cleaning chores will be accomplished on non-duty days. The Space Station crew loading plan seems intended to keep the crew load close to an 8 hour day and 40 hour week. (9)

We would expect the crew to be busy with exploration while on the surface of Mars, but even on Mars excess crew time may be a byproduct of the mission plan. The roughly 18 month duration of the expected surface stay and the high resource requirements and risk of surface exploration compared to remaining in the habitat may limit the crew time for exploration and so allow extensive operations and maintenance work and free time. If the crew is sized to provide the right skill mix, group dynamics, peak labor capacity, or emergency response, the crew could be larger than needed for routine labor. High energy Mars transfers with a very short one month stay have been suggested, indicating we might pay higher mass and cost and severely limit exploration time to reduce risk. It’s as if the expected 18 month surface stay uses Mars itself as a slow cheap transit vehicle, spending crew time to save cost.

HOW MUCH TIME SHOULD A SPACE CREW WORK?

The possible over scheduling of space crew time is definitely a serious issue. NASA in the early days assumed that duty schedules would be long and arduous and has tended to cram schedules. But it was found that heavy workloads were not practical for long duration missions, especially during the Skylab 4 crew rebellion due to over work. The planned workload on Mir had to be reduced. (10, 11)

But it is also clear that having excess crew time is a perhaps more dangerous problem. Stimulating, challenging, meaningful work is of extreme importance for crew morale. Boredom can be worse than being too busy and it becomes greater as mission duration lengthens. Lack of work is psychologically and socially unhealthy, and may lead to poor performance and personnel difficulties. Spreading the crew a little bit thin may enhance performance, but significant understaffing can have disastrous consequences. Overstaffing is a tempting way to reduce risk. (10) Dr. Norm Thaagard complained of "not having enough to do" when his experiments on Mir were delayed. (11)

The right amount of work is important. The space crew should have a workload adjusted to avoid monotony from under loading and fatigue from overloading. An eight hour work day and five day work week could be considered optimal. (10, 11) The objectives of crew scheduling should include planning the right amount of work. The cost of crew time should be assessed to help achieve an optimum work load.

THE COST OF CREW TIME SHOULD OPTIMIZE WORKLOAD

We should define the cost or ESM of crew time so as to guide mission planning and system design to make the best use of the right amount of crew time. The extremes of over work and lack of work must be avoided. The correct cost and ESM of crew time depends on the demand. We want to set the ESM of crew time so the mission planners and system designers will all together request something like a 40 to 60 hour crew workweek.

If little work is needed, the excess crew time should be a free resource provided at no charge, regardless of the cost originally incurred to provide crew time. It will improve morale if the crew is found meaningful work. The mission design should even pay additional ESM and cost to provide this work. Using crew time then has a negative cost.

We could treat crew time as oversubscribed and limited during mission planning if we want to ensure there is enough time available during operations. We do not want to encourage a large demand by setting a zero cost, since we may then have to provide additional crew time at a very high cost. But we should treat crew time as free if we are certain there will be excess. The ESM that should be charged per hour for crew time depends on the total demand for crew time. The ESM of crew time should be the maximum if crew time is scarce and zero if the work is insufficient to occupy the crew.

USING COST OF CREW TIME TO OPTIMIZE WORKLOAD

How can we do this in practice? Let’s assume that we are helping a group of engineers design a human space mission. As usual, the engineers responsible for individual systems receive initial allocations of mass, volume, power, cooling, and crew time. These will be adjusted as design proceeds. To optimize use of all these different resources we suggest allowing the engineers to trade between them according to their mass equivalents. We can start by allocating all available crew time, assigning the full mission mass as the cost of all crew time, optimizing the user requests at that price, and then if demand is too low we can gradually reduce price to increase demand to the level we want. See figure 1 below. The heavy slanted line represents the total demand for crew time at different costs or mass equivalents. The initial cost of 1,000 kg per hour per crewmember per week results in using only 50 hours per week, so we cut the price to 700 kg.

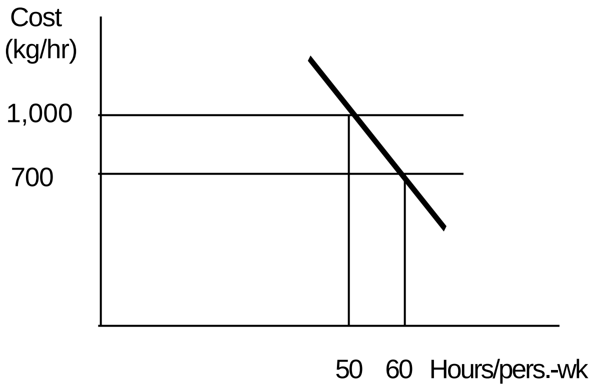

Figure 1. Reduced cost increases use to 60 hours.

If the demand for crew time is much lower, as in figure 2 below, we reduce the price to zero so that as much time is used as possible.

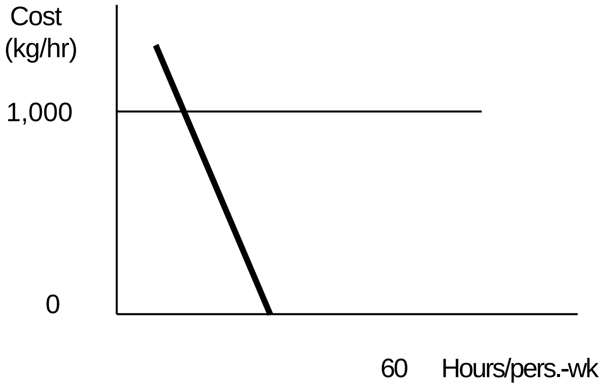

Figure 2. Demand less than 60 hr pr week at zero cost.

If the demand is much higher, so that more than 60 hours per week is requested at the initial price, we increase crew size. See figure 3. The engineers using crew time are willing to pay enough mass to fly additional crew.

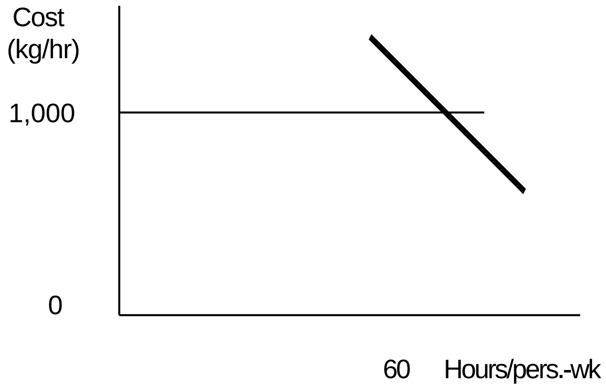

Figure 3. Demand greater than 60 hours at maximum cost.

Rather than adjust the cost of crew time in steps as above, we can set up a cost versus quantity curve for crew time and publish it, as in figure 4 below. Based on this cost curve, the crew time users make a guess on the price and then request a certain amount of crew time. The cost of crew time for all the users is determined by the total demand. The cost curve in figure 4 gives the same prices for different demands as the process described above. The price is zero for demands of less than 60 hours per crew member per week, increases from zero to the full mass at 60, then remains at the maximum.

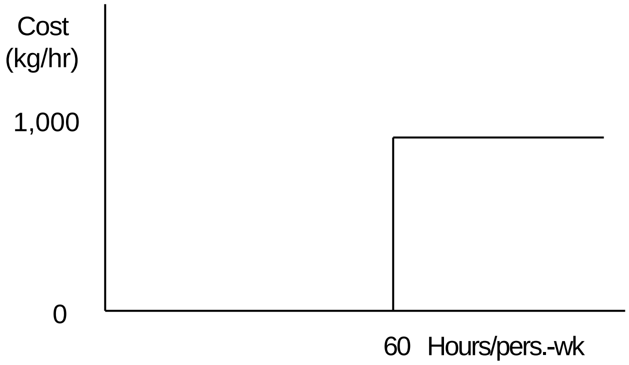

Figure 4. Cost charged versus quantity.

The abrupt switch from 0 to 1,000 kg per hour is destabilizing, as demands may alternate below low and high. To help the price converge, we can increase price gradually between 40 and 60 hours, as shown in figure 5.

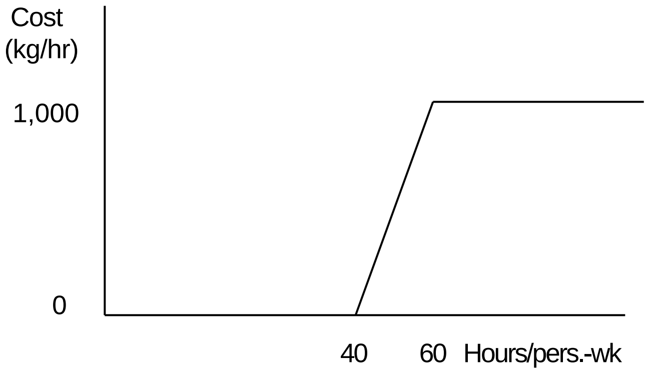

Figure 5. Gradually increasing cost.

The large increase in price from zero to maximum from 40 to 60 hours per week is a way to solve the crew time planning problem. It is likely that without specific action being taken there will be either a large excess or a large deficit of crew time. The mission planners should strive to have the maximum anticipated demand for crew time be just slightly less than the desired workweek, as shown in figure 6. The crew then will have some slack and flexibility during actual operations. To get exactly to some particular point, we may have to use a vertical demand curve as in figure 4, which is equivalent to the time allocation approach often used. If we achieve this desired final crew time demand, the final price of crew time will be small. This means that design changes requiring only small additional crew time, such as going from a batch to continuous reactor as in table 1 above, should not have a large impact. The high cost of sending humans to Mars is justified by science and exploration, done in the highest value crew hours, not in operating reactors, done in the lowest value hours.

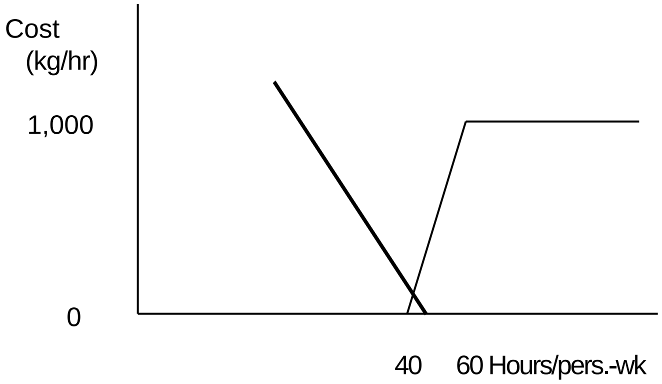

Figure 6. Desired final crew time demand.

CONCLUSION

We can compute the cost or ESM for crew time just as we do for volume, power, or cooling. Nearly all the cost of a human mission is needed to transport and provide for the crew. But if this cost is not incurred with the explicit intent to provide work hours, it may not be appropriate to charge the full cost for each hour worked. During mission planning, the cost of crew time should be set so that the crew has the right amount of useful work. Accomplishing this using a schedule of increasing cost for higher total crew time may give a better allocation of crew time and a more efficient trade-off of crew time for other resources than explicitly allocating the various resources one-by-one to the individual systems.

Because the final assessed cost or ESM of crew time should be high or low for different missions depending on the total demand for crew time, we can provide only general guidance to subsystem hardware designers. The cost of crew time will be very high if the total demand is high. Designs should make the same minimum demands on crew time as on other scarce resources. But crew time can be expected to be provided reasonably for mission work, necessary operations, and risk reducing maintenance. If the total demand is low, the excess crew time may be made available at no cost.

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REFERENCES

1. Guerra, L., and R. Shishko, “Estimating the Cost of Crewed Space Systems,” p. 941, in W. K. Larson, and L. K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design,* McGraw-Hill, New York, undated, 2000.

2. Doll, S., and P. Eckart, “Environmental Control and Life Support Systems (ECLSS),” pp. 565-6, in W. K. Larson, and L. K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design,* McGraw-Hill, New York, undated, 2000.

3. Julie A. Levri, David A. Vaccari, and Alan E. Drysdale, "Theory and Application of the Equivalent System Mass Metric,” SAE Paper No. 2000-01-2395, 30th International Conference on Environmental Systems, Toulouse, France, July 10-13, 2000.

4. John Hogan, Sukwon Kang, Jim Cavazzoni, Julie Levri, and Cory Finn, “A Simulation Study Comparing Incineration and Composting in a Mars-Based Advanced Life Support System,” presentation MA 87, 4th International Conference on Life Support and Biosphere Science, Baltimore, Maryland, August 6-9, 2000.

5. John Hogan, email personal communication, Sept. 2000.

6. Stilwell, D., R. Boutros, and J. H. Connolly, “Crew Accomodations,” in W. K. Larson, and L. K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design,* McGraw-Hill, New York, undated, 2000.

7. Connolly, J. F., “Mars Design Example,” in W. K. Larson, and L. K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design,* McGraw-Hill, New York, undated, 2000.

8. Pearson, A. O., and Grana, D. C., Preliminary Results from an Operational 90-Day Manned Test of a Regenerative Life Support System, pp. 366, 372, 381, NASA SP-261, 1971.

9. SSP 50391, Crew Loading Report, International Space Station Program, Baseline, July 1999.

10. Connors, Mary M., Albert A. Harrison, and Faren R. Akins, *Living Aloft: Human Requirements for Extended Spaceflight*, pp. 119, 123, 124, 126, 128, 131, 172, 290, 323, NASA SP-483, 1985.

11. Freeman, Marsha, *Challenges of Human Space Exploration*, pp. 8, 9, 12, 180, 188, 220, Springer, London, 2000.

CONTACT

Harry Jones, Ph.D.
Mail Stop 239-8
NASA Ames Research Center
Moffett Field, CA 94035-1000
Phone: 650-604-5518
e-mail: hjones@mail.arc.nasa.gov