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MEDICAL AND PHYSIOLOGICAL CONSIDERATIONS FOR A HIGH-ALTITUDE MMA SITE

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ABSTRACT

At the 5000 m altitude of the proposed MMA site in Chile the partial pressure of oxygen of the inspired gas in the lung is only 53% of its sea-level value. The resulting hypoxia causes a number of medical and physiological effects which must be considered in the planning of the instrument. In this report some of the existing studies of these effects are reviewed in order to predict, where possible, their severity in the MMA situation. An operating scenario is proposed which makes the construction and operation of the MMA feasible at this high elevation. The two key features of this

scenario are the establishment of a low altitude Operations Support Base (OSB) at 2440 m and the oxygen enrichment of the air inside the buildings on the 5000 m site. Workers will sleep at the OSB and complete as much work as possible there, making the 1.25 hr drive to the site only when necessary. Workers who start to develop any of the high altitude illnesses can be immediately taken down to the OSB where the condition will quickly reverse. The oxygen in the site buildings will be enriched to 26 % oxygen, providing an effective working altitude for indoors workers of 3500 m (11500 ft). Although many outdoor workers will acclimatize sufficiently so that supplemental oxygen is not required, those workers who require it will be supplied with portable oxygen from a lightweight tank feeding nasal cannulas.

The successful operation of high altitude facilities of comparable complexity to the MMA provides reassurance that the proposed MMA operation is feasible. The complex of large telescopes at the Mauna Kea Observatory at 4215 m (13800 ft) are successfully operated and maintained by workers who, for the most part, commute daily from sea-level. Although the high altitude problems are somewhat worse at 5000 m than they are at 4215 m, the higher sleeping altitude of the MMA workers and the use of oxygen enrichment should make up for this difference. Large mines employing many hundreds of workers are now successfully operating in Chile at elevations up to 4600 m. These mines employ the most modern technology requiring a high level of technical ability from the workers. The technique of oxygen enrichment is now being used at these mines.

1. INTRODUCTION

At an altitude of 5020 m (16470 ft) the proposed MMA site near San Pedro de Atacama in Northern Chile would be the highest year-round-operated astronomical site in the world. Although some cosmic ray observatories have been operated intermittently at higher altitudes, and some observatories have operated at altitudes up to 4800 m in the past (Putnam and Houston,1995), the current highest major observatory site in full-time operation is Mauna Kea in Hawaii at 4215 m. The barometric pressure on the MMA site is 423 torr (564 mb) , 56% of sea-level pressure. This compares with 61% of sea-level at the Mauna Kea Observatories (MKO) where the pressure is 465 torr. A critical quantity that determines the ability of workers to function on a high altitude site is the partial pressure of oxygen, Po_2, in the inspired air inside the lung. Since the air inside the lung is saturated with water vapor, inspired Po_2 decreases slightly more rapidly with altitude than does barometric pressure. Inspired Po_2 on the MMA site is 53% of sea-level compared to 59% on Mauna Kea. Thus, the MMA site has 10% less oxygen than MKO. The scale and technical complexity of the MMA is such that the feasibility of constructing, commissioning and operating the instrument in this hypoxic atmosphere needs to be carefully considered. In this report we review the medical and physiological considerations for personnel working at high altitude and propose an operating scenario for the MMA which will allow workers to perform their duties safely and productively. In summary, the proposed operations scenario is centered around the MMA site at 5000 m and an Operations Support Base (OSB) located near San Pedro de Atacama at approximately 2500 m. Most MMA workers will work approximately on a week-on week-off basis. They will spend their week off at their family home and during their work week they will live and sleep at the OSB. As much work as possible will be done at the OSB but those employees who have work to do on the MMA site will commute to it from the OSB on either a daily or as-needed basis.

The effects of high altitude on humans have been extensively studied because of their importance in the areas of mountain recreation, aeronautics and military and mining operations. Additionally, they are actively studied by the medical community because the body’s response to the hypoxic stress of altitude can lead to greater understanding of various pulmonary and cardiovascular diseases which deprive the body of oxygen. Discussions of the medical and physiological problems associated with high altitude are available in the non-medical literature (Cudaback, 1984; Forster, 1984; Houston, 1987; Putnam and Houston, 1995). In the recent medical literature Hackett and Roach (1995) give a good review of the subject and a detailed treatment is given by Ward, Milledge and West (1995). In addition, a comprehensive bibliography of high altitude medicine references, containing more than 4700 entries, is maintained by Roach, Houston and Hackett (1996).

It is important to note that the majority of previous research has considered the response of people to long term (several days at least) exposure to altitude, whilst workers on the MMA site will cycle on a daily basis between 5000 m and their sleeping accommodations at about 2500 m. Additionally, it is likely that many of the workers will cycle on a weekly basis between the MMA and their family homes at sea-level. Whilst there have been a few studies of such intermittent exposure to altitude (Forster, 1984 (4200 m); Jimenez, 1995 (up to 4600 m); Jalil et. al., 1995 (up to 4600 m)) its consequences are not as well understood as longer term exposure and because of this uncertainty the MMA must be prepared to be flexible in its planning for high altitude operation. Of the published reports the studies of Forster (1984) into the effects of altitude on 41 shift workers at the United Kingdom Infrared Telescope (UKIRT) at 4200 m on Mauna Kea comes closest to the MMA situation. The UKIRT shift workers lived for 5 days at sea-level then spent 5 days working at the telescope for 8.5 hrs, descending each evening to sleep at Hale Pohaku (3000 m). Results for the UKIRT shift worker and other studies are discussed below.

2. MEDICAL AND PHYSIOLOGICAL EFFECTS OF HIGH ALTITUDE

In this section we provide a brief summary of some of the information contained in the references listed above. First we discuss the changes that occur in the body upon exposure to altitude and the process of acclimatization. Then we mention some of the areas of human performance that are affected by the hypoxia of altitude including exercise, sleep and mental ability. Finally we review the three principal illnesses of high altitude: acute mountain sickness (AMS), high altitude pulmonary edema (HAPE) and high altitude cerebral edema (HACE).

2.1 NORMAL RESPONSE TO HYPOXIA

To allow visitors to the MMA site to understand the changes occurring in their bodies, we list below the principal responses of the body to the reduced partial pressure of oxygen at altitude. Where possible we quantify the effects with "typical" or "average"numbers but it must be emphasized that there can be large differences in the responses of different individuals. Where the data exists we give numbers for Mauna Kea as well as the MMA site in an attempt to answer the question "how much worse will the altitude problems be at the MMA site, as compared to MKO".

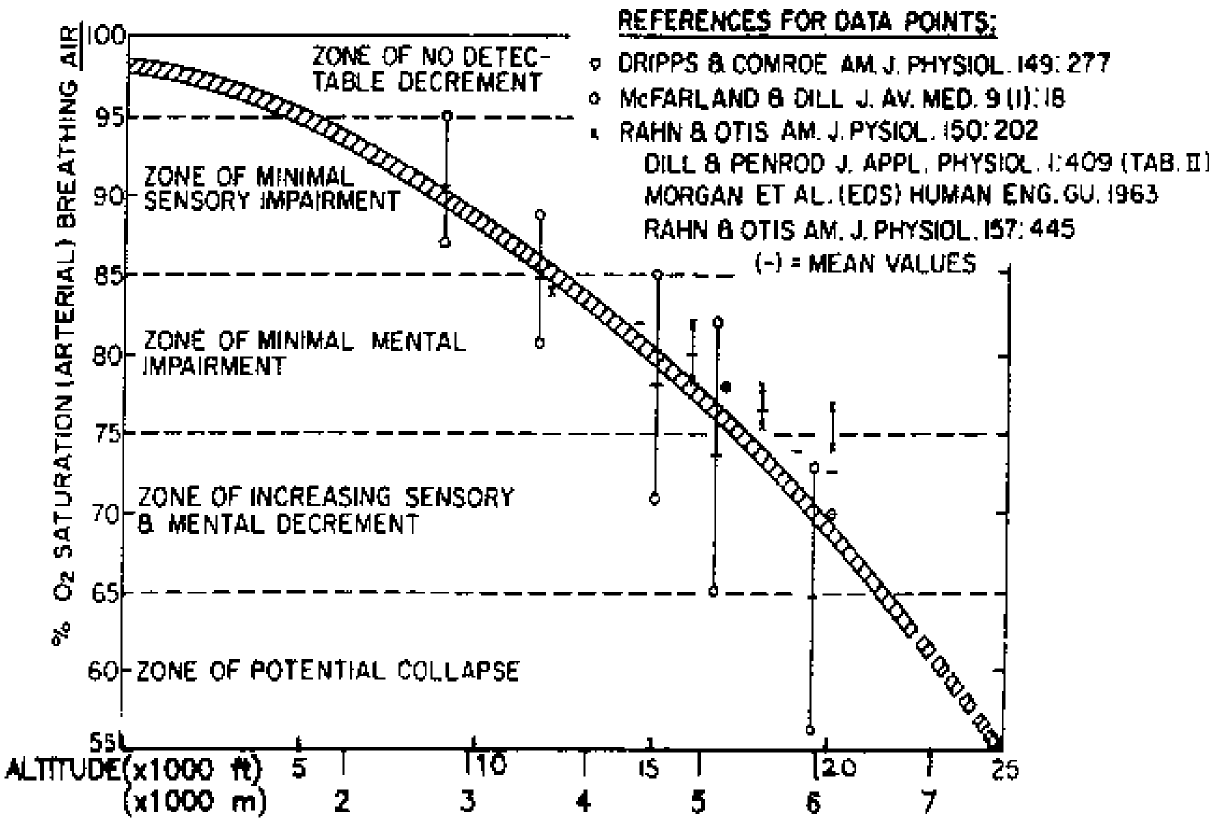

Figure 1 The relationship between mean arterial oxygen saturation (%) and altitude for several performance tests in unacclimatized subjects (from McFarland, 1972).

One measure of the amount of oxygen available for use within the body is arterial oxygen saturation Sao_2, the percentage of binding sites of hemoglobin molecules that are carrying oxygen. This quantity can be easily measured using a finger or ear oximeter. Within a minute of exposure to altitude Sao_2 begins to drop. Typical values for Sao_2 as a function of altitude for unacclimatized individuals are shown in Figure 1. Figure 1 also indicates the general level of human performance impairment expected at high altitude, but note that the boundaries between the different levels of impairment are very approximate and vary between individuals. Over a period of a few days at altitude, by the adjustments mentioned below, the body will acclimatize and it can be expected that at 5000 m Sao_2 will rise from an initial value of about 75% to about 85%. This compares with about 90% measured on acclimatized workers on Mauna Kea (Olsen, 1995a).

Ventilation (volume of air breathed/minute) increases so as to reduce the partial pressure of carbon dioxide (Pco_2) in the alveoli, thereby allowing alveolar Po_2 to increase. This response may begin immediately at altitudes as low as 1500 m and at 5000 m results in a resting ventilation rate approximately 60% higher than sea-level after several days at altitude.

As alveolar Pco_2 is reduced, carbonic acid in the blood is also reduced making the blood more alkaline. The kidneys respond by increasing bicarbonate excretion in order to return blood pH to near its normal value. This response starts within 24 hrs and lasts for several days.

Heart rate and blood pressure initially increase with exposure to altitude then slowly return towards low altitude values as acclimatization proceeds.

On time scales of days to tens of days the concentration of oxygen-carrying red blood cells is increased by the production of new red blood cells resulting in a hematocrit about 10 % or more higher than sea-level.

2.2 ACCLIMATIZATION

Altitude acclimatization is the process of physiological change in the body that increases oxygen delivery to the cells. The most important changes are those mentioned in Section 2.1 above and they take place on time scales of hours to days and, in the case of additional red blood cell generation, weeks after exposure to altitude. The degree to which an individual's body is able to make these changes quickly (hours to days) determines whether he will be able to function well or whether he will be unable to shake off the initial symptoms of AMS (see section 2.6) and be unable to work effectively. The particular reasons why some people are able to acclimatize well and others poorly are not well understood. Good physical fitness is not a guarantee that a person will acclimatize well. The only reasonably reliable indicator that a person will do well at altitude is that they have previously done so, although this is not a guarantee.

Predicting the amount of acclimatization to be expected for MMA workers is complicated by the intermittent nature of their altitude exposure. Upon descent to low elevation the acclimatization adjustments of the body disappear at approximately the same rate as they are gained (Hackett and Roach, 1995). Thus a few days at sea-level may be enough to make a person susceptible to high altitude illness upon reascent, although this is less likely if he has previously been able to acclimatize successfully. At the beginning of their work week those workers who have spent their week off in homes at sea-level, for example in Antofagasta or Santiago, will have lost some, but probably not all, of their acclimatization. Workers who have spent their week off at homes in the local area such as San Pedro de Atacama or Calama, both at 2500 m, will retain more of their acclimatization from the previous work week. During their work week those workers who cycle every day from the sleeping accommodations at 2500 m to the 5000 m site will achieve acclimatization equivalent to an altitude somewhat less than 5000 m whilst those workers who ascend to 5000 m on only occasional work days will achieve reduced acclimatization. In any case it seems likely that no workers will become fully acclimatized for 5000 m and this is one of the reasons why it is planned to provide supplemental oxygen on the MMA site (see Section 3).

2.3 SLEEP

Quality of sleep is significantly decreased at altitude with shortened periods of sound sleep and increased frequency of arousal. A particular problem is "periodic breathing" in which ventilation rates oscillate between high and low values. During the periods of low ventilation Sao_2 can fall significantly below the average value so that the degree of hypoxia experienced by the body during sleep can correspond to an altitude higher than the sleeping altitude. This is the basis for the well known climbers rule " climb high sleep low". As an example of high altitude sleeping problems studies of 122 acclimatized miners sleeping at 4300 m on approximately a week-on week-off basis at a mine 300 km from the MMA site in Chile (Jimenez, 1995) gave quality of sleep statistics as shown in Table 1 below.

Table 1. Quality of Sleep, 1st and 5th night at 4300 m and Sea-level of 122 Acclimatized Mining Workers Exposed to Altitude During Their Work Week (from Jimenez. 1995)

% OF WORKERS	AT SEA	LEVEL	AT 4300	M
	1st night	5th night	1st night	5th night
Excessive time to fall asleep (> 30 min)	8.3%	10.0%	45.1%	15.9%
Reduced total sleep time (< 5 hrs)	27.8%	23.3%	65.7%	63.5%
Excessive awakenings (> 3)	11.1%	26.7%	54.9%	19.0%
Early waking	11.1%	16.7%	20.6%	11.1%
Perception of inadequate resting	41.7%	26.7%	61.4%	30.0%
Perception of general poor quality of sleep	16.7%	20.0%	61.8%	28.6%

The poor quality of sleep to be expected for workers sleeping at 5000 m is one of the most important reasons for locating the OSB and the MMA sleeping accommodations at relatively low elevation. The question arises as to what is the best altitude for the location of the OSB. This is basically a tradeoff between sleep quality, travel time and acclimatization. An OSB location near San Pedro de Atacama at an elevation of 2500 m and a distance of 50 Km from the MMA site offers the advantage of good sleep for all employees. An OSB location at 3000 m and a distance of 35 Km from the site would allow those workers ascending to the 5000 m site to acclimatize better and have less travel time but at the expense of reduced quality of sleep. An additional consideration is that more workers will develop symptoms of AMS at the beginning of their work week if the OSB is located at 3000 m (see Section 2.6). At this time we favor locating the OSB at 2500 m rather than 3000 m because it is expected that only a fraction (perhaps 20%) of the people living at the OSB will in fact travel frequently to the 5000 m site once routine operation is achieved. However, this is not a clear cut decision and if significant technical advantages are identified for the higher OSB location, for example shorter fiber optics or antenna transporter runs, the medical arguments are not so strong as to completely rule it out.

A few individuals who are particularly sensitive to altitude may have difficulty sleeping on their first night or two even at 2500 m. For these individuals acetazolamide (diamox), 125 mg taken at bedtime, diminishes periodic breathing, improves oxygenation, and is a safe agent to use as a sleeping aid before acclimatization (Hackett and Roach, 1995).

2.4 EXERCISE

The extent to which the human body can do hard aerobic work is determined by the maximum rate at which the body can take up oxygen. This maximal oxygen consumption drops significantly at altitude with little improvement with acclimatization. Work ability reductions of 20 % and 25 % for Mauna Kea and the MMA site respectively are reported by Ward, Milledge and West (1995, their Figures 10.7 a and 10.7b). It is clear that the ability of workers to perform hard labor will be significantly reduced at the MMA site and this reduction in efficiency must be allowed for. PaO_2 drops temporarily upon exertion causing panting and reduced mental ability (see Section 2.5). To reduce this efficiency loss we will plan on providing supplemental oxygen to workers on the MMA site, particularly in those situations where hard labor must be accompanied by careful decision making.

In order to help recover from breathlessness caused by exertion, some people use a technique of breathing out through pursed lips in order to increase the barometric pressure inside the lung slightly. This technique is sometimes called "pressure breathing" or "grunt breathing" (Houston, 1987). However, the technique is awkward and because the amount of barometric pressure increase achievable is very small, taking a few deep breathes is just as effective (Houston, 1987 pg 164).

2.5 MENTAL ABILITY

The hypoxia of altitude reduces a person's mental abilities because of the reduced oxygen supply to the brain, the effect often being described as similar to slight intoxication. The technical complexity of the MMA makes this effect of particular concern. There are a number of studies of the severity of the effect although researchers point out that it is difficult to obtain reliable results because of the difference between individuals and because of the tendency of subjects to "try harder" during tests at altitude.

Table 2. Mental ability expressed as a fraction of ability at sea-level for unacclimatized individuals (from McFarland, 1972).

Altitude (m)	Visual sensitivity	Attention span	Short term memory	Arithmetic ability	Decision making ability
2500	83%	100%	97%	100 %	100%
3500	67%	83%	91%	95%	98%
4200	56%	70%	83%	92%	95%
5000	48%	57%	76%	86%	90%

Although anecdotal evidence of reduced mental ability due to the altitude at the Mauna Kea observatories abounds, the limited measurements of Forster (1984) on UKIRT shift workers showed little quantitative reduction in ability. Numeric memory was reduced to 88% of its sea-level value on the first day of work at altitude with improvement over the next few days so that by the fifth day there was no significant difference from sea-level performance. Measurements of motor speed and information recording showed no statistically significant difference from sea-level performance on any day. McFarland (1972) has compiled the results of several studies at various altitudes and uses these to quantify mental ability loss as a function of altitude. His general summary curve is shown above as Figure 1 and Table 2 gives numbers taken from his detailed curves. The results are for unacclimatized individuals and are therefore presumably applicable to MMA workers at the beginning of their work week. The numbers for 3500 m are included to indicate the expected performance of workers in MMA buildings containing a 26 % oxygen atmosphere. Visual sensitivity is a measure of the lowest light level detectable to the eye and its reduction at altitude is caused by brain hypoxia.

Tests by Sharma (1975) (see Figure 17.3 of Ward,Milledge and West, 1995) on the psychomotor (intricate hand/eye coordination) abilities of acclimatized Indian soldiers at 4000 m showed performance at 63% of sea-level after one month improving to 83% after several months. Jimenez (1995) has tested 26 professional and technical level acclimatized mining workers who were working on approximately a week-on week-off basis at 4500 m. In the area of general cognitive aptitude, spacial aptitude and mathematical reasoning were reduced by 13% and 19% respectively whilst numeric aptitude and verbal aptitude did not give statistically significant results. In the area of mental performance, attention ability was reduced by 11% whilst concentration and memory did not give statistically significant results.

From the limited available data described above it seems reasonable to assume that the kinds of mental skills that workers on the MMA site will need to solve complex technical problems will be reduced by approximately 10% to 30%. It is common for high-altitude workers to deny that any such reduction is in fact occurring so it will be important to train workers to accept its presence and prepare for it by increased use of plans and checklists prepared at the OSB and by extensive checking of work by partners and supervisors on the MMA site. The common experience of technical workers at high altitude is that accurate work can be done, particularly if detailed protocols are written out, but it takes longer and more concentration is required. Problem solving is particularly difficult and this is where errors are most likely. The principal way in which it is planned to respond to the problem of reduced mental ability is to provide an oxygen enriched atmosphere in those situations where it is required (see Section 3 below). As shown by the 3500 m entries in Table 2, workers breathing an atmosphere in which the oxygen concentration is increased from its natural 21% up to 26% should suffer very little mental impairment.

Tests on mountaineers climbing at extreme altitudes (typically over 7000 m) indicate that the hypoxic insult to the brain causes some residual loss of mental ability (Hornbein et.al., 1989; Fitch, 1995; Ward, Milledge and West, 1995). At the lower altitude of the MMA site there is no indication of any such residual loss.

2.6 ACUTE MOUNTAIN SICKNESS (AMS)

Acute mountain sickness is the most common and least dangerous of the various illnesses caused by the hypoxia of high altitude. It is characterized by headache, fatigue, insomnia, loss of appetite, dizziness, palpitations and nausea. Symptoms begin a few hours after ascent and typically disappear after a day or two. Reports of its occurrence as a function of altitude predict that about 20% of workers will experience symptoms at 2600 m and about 50% will experience symptoms at 5000 m (Hackett and Roach, 1995; Roach et al, 1995) . Tests on UKIRT shift workers (Forster, 1984) gave the occurrence of symptoms shown in Table 3.

No treatment is necessary for most people who will experience little more than a mild headache. Rest is advisable for severe cases, as is descent to lower altitude because severe AMS can progress to HAPE or HACE. Acetazolamide (Diamox) is effective in reducing the incidence of AMS. It inhibits carbonic anhydrase, the enzyme that catalyzes the reaction of CO_2 with water to form carbonic acid, and the net result is a metabolic acidosis which stimulates ventilation. The drug has several side effects (diuresis (increased urination), tingling of the fingers and toes, carbonated beverages taste flat) and should be used only if needed. It is a prescription drug and the dosage is 125 mg to 250 mg twice a day. It can be taken prior to ascent or after symptoms begin at altitude. Analgesics such as aspirin and acetaminophen (Hackett and Roach, 1995) or ibuprofen (Broome et al, 1994) can be taken for relief of the headache. It can be expected that a small fraction of workers will not adapt well to the 5000 m altitude and these employees should be used for tasks not requiring ascent to the high site.

Table 3. Occurrence of AMS symptoms in UKIRT shift workers working at 4200 m and sleeping at 3000 m

Symptom	Day 1	Day 5
Shortness of breath on exertion	50%	21%
Headache	41%	10%
Insomnia, lethargy, poor concentration, forgetfulness	20%	-
No symptoms at all	20%	60%

2.7 HIGH ALTITUDE PULMONARY EDEMA (HAPE)

HAPE is a dangerous illness involving the accumulation of fluid in the lungs. The mechanism of HAPE is probably a large increase in pulmonary artery pressure which damages the walls of some capillaries. It occurs much less frequently than AMS and studies of its incidence (Hackett and Roach, 1995) suggest that incidence in the MMA situation might be in the range .01% to .1%. There have been several cases of HAPE on Mauna Kea in which the patients developed the condition on about the third day of working at altitude, even though they were only at altitude during working hours and were sleeping at 3000 m at Hale Pohaku. The primary symptom is extreme shortness of breath and subjects may cough up pink frothy fluid. The condition often worsens during the night. The primary treatment is to immediately take the patient to lower altitude (in the case of the MMA, down to the OSB). Oxygen should be given and nifedipine is valuable because it reduces pulmonary artery pressure. The condition develops sufficiently slowly that there will be time to take the patient off the site before the situation becomes critical. To ensure that evacuation is always possible a "two man rule" and a "two vehicle rule" should be observed on the site at all times. As an emergency measure, in the event that someone is stranded on the MMA site or on one of the nearby peaks, a portable hyperbaric bag (Gamow bag) should be stored on the site. Such lightweight, fabric bags have proven effective in providing first aid for HAPE cases where the patient cannot be immediately taken to lower altitude. The patient is placed in the bag and the pressure inside the bag is manually increased by a few psi. These bags are available from mountaineering medical outfitters (e.g. Chinook, 1996).

2.8 HIGH ALTITUDE CEREBRAL EDEMA (HACE)

HACE is a dangerous illness involving increased pressure on the brain. It is rare and incidence can be expected to be much less than HAPE. It often begins like AMS with headache, nausea, loss of appetite, vomiting and photophobia, but progresses to ataxia (loss of muscle control), irrationality, hallucinations and clouding of consciousness. The primary treatment is to take the patient to lower altitude as quickly as possible and the condition develops sufficiently slowly so that there will be time to do this. Oxygen should be given and dexamethasone is of value.

2.9 COMMON CONDITIONS AGGRAVATED BY HIGH ALTITUDE

The hypoxia of altitude aggravates a number of common conditions which require subjects to either be cautious or completely abstain from visits to high altitude. These conditions are listed below (from Hackett and Roach, 1995). This list may not be complete and it is recommended that all visitors consult their physician before working on the MMA site.

Caution:
Moderate chronic obstructive pulmonary disease (COPD)
Compensated congestive heart failure (CHF)
Sleep apnea syndromes
Troublesome arrhythmias
Stable angina/coronary artery disease
Pregnancy
Sickle cell trait
Cerebrovascular diseases
Any cause for restricted pulmonary circulation
Seizure disorder (not on medication)
Young children

Avoid high altitude:
Sickle cell anemia (with history of crises)
Severe COPD
Pulmonary hypertension
Uncompensated CHF

3. OXYGEN ENRICHMENT

The various problems of high altitude work, such as reduced mental and aerobic work ability, sleeping difficulties and risk of illness can all be alleviated by placing the workers in either a hyperbaric or an oxygen enriched environment. The pressure in the buildings on the MMA site could be increased to a pressure equivalent to an altitude which would be well tolerated by most workers, an altitude of 3000 m (9800 ft) for example. This would require a pressure increase of 116 torr (2.2 psi) which would result in a force of about 3000 kg (6600 lbs) on a standard sized door. Although increasing the pressure would have the added advantage that it would ease the problem of cooling electronic equipment, the inconvenience of needing an airlock on the building is a significant problem. A reasonable rate of change of altitude for workers with unblocked Eustachian tubes is 200 m/min (Cudaback, 1984), and this would be uncomfortable for workers with blocked tubes. Thus it would take several minutes to pass through the airlock. To our knowledge the only use of a hyperbaric building to solve the problems of high altitude work has been at the Kumptor mine at 4200 m altitude in Kyrghyzstan. In this case the mine operators built a building with a positive pressure of 2 psi but have experienced many logistical problems with its operation and are now planning to change to an oxygen enrichment system . Oxygen enrichment is a practicable solution that is now being adopted as a measure to improve the work environment of several mines at high elevation.

The fundamentals of oxygen enrichment as a means of improving the efficiency of high altitude workers were summarized by Cudaback (1984) and discussed in more detail by West (1995). The key point is shown in Figure 2, taken from West (1995), which shows the equivalent altitude (as defined by the partial pressure of oxygen of inspired gas) as a function of the fractional oxygen enrichment. Figure 2 shows that at 5000 m, for each percentage point increase in oxygen concentration (increasing from 21% to 22% oxygen concentration is an increase of one percentage point), the effective altitude experienced by the body decreases by 300 m. Thus, if the oxygen concentration in the buildings on the MMA site is increased from its natural 21% up to 26%, the altitude effects on the workers in the buildings will be the effects expected for 3500 m, which should be acceptable. The choice of 26% oxygen is a compromise between competing requirements. Improved performance could be obtained with a higher concentration. However, a higher concentration would reduce the degree of acclimatization achieved by indoors workers who must also work outdoors and it would increase the cost and potential fire risk (see Section 3.3).

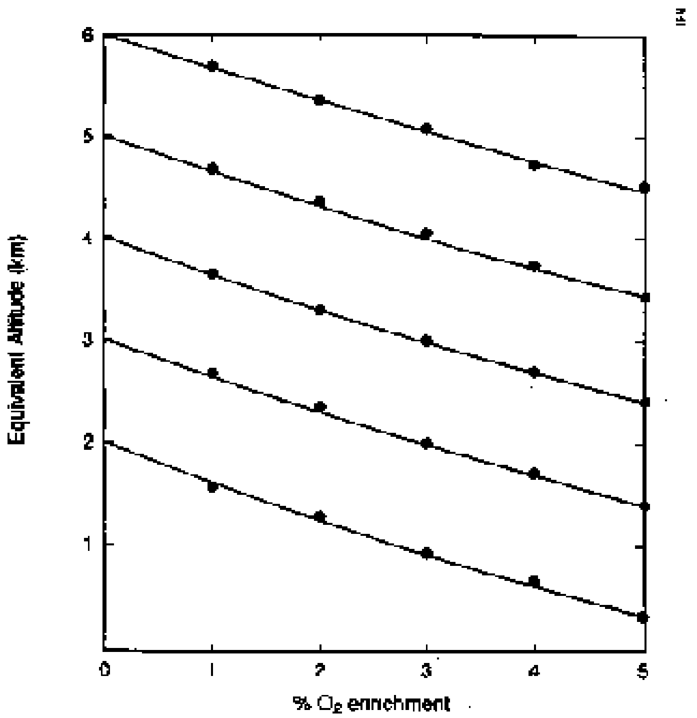

Figure 2. Reduction of equivalent altitude by oxygen enrichment. The equivalent altitude is that which has the same Po_2 of moist inspired gas as in air at that altitude. One percent oxygen enrichment means an increase from 21% to 22% oxygen. From West (1995). Curves are drawn for sites at 2, 3, 4, 5 and 6 km altitude respectively.

The technique of oxygen enrichment inside high altitude buildings is just starting to find application. The CFHT and Keck Observatories on Mauna Kea designed some of their work space at 4200 m to allow for oxygen enrichment, but neither of these systems were ever put into operation. Discussions with CFHT and Keck personnel suggest that the principal reason that oxygen enrichment was never used was the perception that the altitude problems on Mauna Kea are not sufficiently severe to warrant using the technique. Concerns which are often raised with oxygen enrichment include concerns about possible negative effects on workers moving from inside to outside the oxygen enriched areas and concerns about cost and fire hazard. These issues are addressed below. The first real application of the technique appears to be at the El Tambo mine at an altitude of 4300 m in Chile (West, 1996a). At this location the air in a 16 room dormitory had its oxygen concentration increased to 24-25%. Controlled tests on the occupants have shown that the expected improvements in sleep quality have been achieved. An unexpected finding was that a series of sophisticated psychometric tests made on the miners during the day after the test night by a group of industrial psychologists showed improvement in all six of the tests, though in some cases the improvement was very small. The tests included ability to concentrate, short term memory, visual perception, attention span, auditory memory and topographical memory. Since there is no obvious way that increased oxygenation during the night could be carried over to the following day (since the body's stores of oxygen are very small) it seems that the improved night's sleep was responsible for the better measurements. The mining management are very pleased with the results and are planning to use oxygen enrichment in their large dormitory facility consisting of 850 beds. Tests are underway to look at the effects of oxygen enrichment during the day in control rooms, laboratories and even in the cabins of the large trucks and mechanical shovels.

One of the arguments often given for not oxygenating high altitude buildings is that the workers in them will acclimatize less. Since MMA workers will be exposed to altitude on a week-on week-off basis, their bodies will spend the first part of each work week reacclimatizing after their week off. We believe it is better for them to work in an oxygen enriched building and to experience very few altitude problems at all, and the degree of oxygen enrichment is sufficiently low (equivalent to 3500 m altitude) so that significant acclimatization can still take place. Workers who have to work both indoors and outdoors can use portable oxygen if necessary (see Section 3.2 below) and we will keep open the possibility of oxygenating such "outdoor" areas as the antenna assembly building (it will have closable doors), the operator cabs of special vehicles such as the antenna transporters and the antenna receiver cabins. Workers who move from inside an oxygenated area to outside and who do not use portable oxygen should not exert themselves for a few minutes while their ventilation rate increases.

Another consideration in the use of oxygen enrichment is the need to overcome the "macho" attitude of some people which drives them to tolerate the altitude effects without supplemental oxygen if at all possible. Due to the intermittent nature of their altitude exposure it will not be possible for MMA workers to become fully acclimatized to 5000 m altitude and so their mental and aerobic work capabilities will be reduced. If they can be returned to full efficiency by oxygen enrichment they must be encouraged to use it in order to maximize the efficiency of the MMA operation.

3.1 TECHNICAL ASPECTS OF OXYGEN ENRICHMENT

One of the reasons that oxygen enrichment is now feasible is that it is no longer necessary to provide the oxygen from liquid oxygen in bottles. A molecular sieve is capable of providing the oxygen in a more convenient and economic way. In a molecular sieve air is pumped through a ceramic filter which preferentially absorbs nitrogen increasing the concentration of oxygen in the air exiting the filter. Air with an oxygen concentration of up to 90% can be produced and used to oxygenate the air in the ventilation system of a building to the desired level of oxygen concentration. Molecular sieve oxygen concentrators usually work in pairs so that, while one unit is producing oxygen, the other is regenerating its filter by reversing the direction of air flow at low pressure. West (1995) shows that 100 L/hr of 90% oxygen concentration air is needed for each percentage point increase in oxygen concentration for each person in the oxygenated area using a minimal, but acceptable, level of ventilation. Thus a two man office with 26% oxygen concentration (a five percentage point increase over the natural 21%) would require about 1000 L/hr of 90% oxygen concentration air. This can be provided by small scale molecular sieve equipment costing about $5000 and requiring about 1400 w of electrical power to operate. Assuming that a worker spends three quarters of his 2000 working hours per year on the MMA site and that the molecular sieve equipment lasts for five years, then the effective annual cost of oxygenation is $550 per worker which is a small fraction of the worker's annual salary. This calculation is based on the use of small scale equipment. The use of larger scale equipment, such as would be suitable for oxygenating the buildings on the MMA site, should increase the efficiency of the system.

3.2 PORTABLE OXYGEN

It is likely that workers who work primarily outdoors, and who are therefore the best acclimatized, will be able to perform most tasks without oxygen. For those workers who work only occasionally outdoors and therefore have less acclimatization, or for outside workers who must perform a task which is mentally or physically particularly demanding, it may be advisable to use portable oxygen. It is proposed to provide this, when needed, by use of a convenient, light weight, back mounted oxygen tank feeding nasal cannulas. With an oxygen supply rate of 2 liters/min (adequate to provide an equivalent altitude of about 3500 m for low levels of exercise), and by using a demand regulator which supplies oxygen only when the user breaths in, a system with a total weight of only 4 kg (8 lb) will supply oxygen for more than 8 hours (Chinook, 1996). A nasal cannula is preferred over a mask because it makes communication easier and is less intrusive. The only problem expected with the use of a cannula is dry nasal passages and this can be cured by a light application of Vaseline. Such nasal cannulas are widely used by medical patients and have also been used for research and mining work at high altitude. A test was performed at the Keck Observatory to evaluate the use of supplemental oxygen supplied by a molecular sieve concentrator feeding a nasal cannula (Faber et. al, 1989). Although no quantitative tests of performance improvement were made, the expected increases in Sao_2 were measured and the equipment was judged to be "useful equipment for Mauna Kea". Padin (private communication, 1996) tested a cannula at 5200 m on Co. Toco beside the MMA site during a site finding visit by a Caltech group. He found that an oxygen flow rate of 4 L/min allowed him to run uphill and 2 L/min was adequate to prevent breathlessness for normal walking. He experienced some dizziness when he terminated the use of the oxygen. This dizziness was probably caused by intense exertion immediately prior to turning off the oxygen. Users of portable oxygen should avoid exertion for a few minutes before and after turning off the oxygen.

A concern sometimes heard with respect to the intermittent use of oxygen enrichment, either in a building or outdoors with a portable oxygen system, is possible harm to the body in rapidly and frequently going on and off oxygen. There is no physiological basis for this concern. Climbers at much higher altitudes often use supplementary oxygen on an intermittent basis and there are no problems with coming off oxygen except the need to be aware that one is breathing a much lower oxygen level and reduce the level of activity for a few minutes.

3.3 FIRE HAZARD

One of the concerns often raised with respect to oxygen enrichment is the possibility of increased fire hazard. Fire, once it is started at high altitude, is particularly dangerous to workers because of the increased risk of asphyxiation. Inhaled smoke further decreases an already diminished oxygen supply, so the time available to evacuate a building before workers become unconscious is reduced. Additionally, the reduced oxygen causes combustion to be less complete resulting in increased levels of carbon monoxide compared to low altitude fires, and carbon monoxide is particularly hazardous at high altitude because it can more easily combine with hemoglobin under hypoxic conditions. Special care should be taken in the design of a high altitude building to provide adequate smoke detection sensors and emergency exit routes for all workers.

The problems of fire hazard in a low pressure, oxygen enriched atmosphere such as that proposed for the MMA buildings are addressed in the National Fire Protection Association (NFPA) Codes for Hypobaric Facilities (NFPA, 1993) and for Oxygen-Enriched Atmospheres (NFPA, 1990). As a general rule, fire hazard decreases as the partial pressure of oxygen decreases, because of the reduced amount of oxygen available for combustion, and increases as the partial pressure of nitrogen decreases, because of decreased nitrogen quenching. Whether or not a particular atmosphere provides increased or decreased fire hazard depends on which of these effects dominate and on the particular material considered for combustion. The NFPA (1993) defines an oxygen enriched atmosphere to have increased fire hazard, in the sense that it will support increased burning rates of materials, if the percentage concentration of oxygen is greater than $23.45/(TP_{atmos})^{0.5}$, where TP_{atmos} is the total barometric pressure expressed as a fraction of sea-level pressure. For the MMA site TP_{atmos}=0.56 so if the oxygen concentration is greater than 31% it would exceed the NFPA threshold. Our proposed oxygen concentration of 26 % is below this threshold, as we might have expected since the partial pressure of oxygen, although increased, is still only 68 % of sea-level oxygen partial pressure. Studies of the burning rates of paper in oxygen enriched hypobaric atmospheres referenced by NFPA (1990, Table 5-6), NFPA (1993, Fig A-2-2) and West (1996b) can be interpolated to predict burning rates of paper in the MMA oxygen enriched atmosphere of 79%, 95% and 75% of sea-level burning rate respectively. Presumably the differences in the burning rates predicted by the three different studies is due to differences in the measurement methods used for the different studies. We have not found published measurements which allow us to predict fire hazard in the MMA atmosphere for solid materials other than paper, but NASA has made measurements in a similar, but somewhat higher risk, atmosphere. A commonly used atmosphere in the Space Shuttle and Space Station is 527 Torr (10.2 psi, 0.69 atmos.) barometric pressure, 30 % oxygen, which is used to promote nitrogen washout prior to entering the low pressure (4 psi) spacesuit atmosphere for extravehicular activity. Burning rates for a number of common materials have been measured (NASA, 1992) at the NASA White Sands Test Facility in New Mexico in this 0.69 atmos, 30% oxygen atmosphere. It is reassuring that NASA considers the risk associated with this oxygen enriched atmosphere, which has a significantly higher partial pressure of oxygen than the MMA oxygen enriched atmosphere, to be acceptable, even for a permanently manned spacecraft such as the Space Station.

The discussion in the previous paragraph was concerned principally with the fire hazard of solid materials. Common sense requires that flammable gases and liquids must not be used in an oxygen enriched atmosphere and such a rule should not create significant operational inconvenience. The relatively small amount of oxygen that is added to the MMA atmosphere probably does not increase the fire risk substantially. For example, NFPA (Fig 5-4, 1990) shows that for a 5 % concentration of butane gas, 80% more energy is required to initiate ignition in a 0.5 atmos., 26 % oxygen atmosphere (very close to the MMA atmosphere) than is required in a 1.0 atmos., 21 % oxygen (sea-level) atmosphere. Volatile liquids require careful handling even without oxygen enrichment. Olsen (1995b) has found that volatile liquids ignite more easily on top of Mauna Kea and their vapors spread more readily than at sea-level. This is due in part to the fact that the flash point of volatile liquids decreases as barometric pressure is reduced. The flash points of typical volatile liquids such as benzene and ethanol are about 8°C lower at 5000 m altitude than at sea-level (NFPB, Fig 3-5D, 1992).

In summary, provided that care is taken in the design and operation of the MMA buildings it does not appear that an oxygen concentration of 26% will cause an unacceptable fire hazard. Since little experimental data exists specifically for the proposed MMA atmosphere, before designing the oxygen enriched MMA buildings it would be wise to perform fire tests on any potentially flammable materials to be used in the buildings. The NASA White Sands Test Facility has the necessary test facilities and is willing to perform these tests and advise on fire protection methods. The use of oxygen enrichment should be limited to those areas that require it, such as control rooms and engineering offices, and the use of combustible materials or volatile liquids in these areas must be avoided.

4. AN MMA HIGH ALTITUDE SCENARIO

On the basis of the information reviewed in the preceding sections we propose the following scenario for the construction and operation of the MMA with respect to the medical and physiological problems of high altitude.

The basic philosophy will be to minimize the number of man-hours actually spent on the 5000 m site. A small test array will be built on a convenient site in the Continental US and as many problems as possible, both hardware and software, will be identified and solved there before the system is used at 5000 m. An Operations Support Base (OSB) will be built close to San Pedro de Atacama (2500 m) and as much work as possible will be performed there rather than on the high site. For the construction phase, for example, we will investigate the feasibility of completely assembling, outfitting and testing antennas at the OSB and then transporting them up to the MMA site on the antenna transporter. All equipment will be designed so that it can be maintained by swapping a "module" rather than by repair in place. Examples of a "module" could be a complete cryogenic receiver, a correlator board, an antenna drive motor or an air-conditioning compressor. All " modules" will be repaired at the OSB. Once routine operation is achieved the array operator will be located at the OSB.

Most MMA personnel will work at the OSB on a week-on week-off basis. During their week off they will return to their family homes, some of which may be at sea-level. During their week on they will live and sleep in comfortable dormitories at the OSB. The OSB should have good living and recreation facilities (cafeteria, gymnasium, swimming pool etc.). Only those workers who have specific work on the 5000 m site will make the 1.25 hour drive to the site. All workers should spend at least one night at the OSB before ascending to altitude. In operations phase it is expected that on most work days only a fraction, perhaps 20%, of the workers at the OSB will go to the site. For those workers not working in an oxygen enriched building on the high site the time at altitude should be limited to 6 to 8 hours.

At the OSB there should be a medical clinic equipped to handle high altitude problems. This will require someone with training in high altitude medical problems who is qualified to administer prescription medications. A supply of the appropriate medications such as oxygen, acetazolamide, dexamethasone and nifedipine should be available. There is already a medical clinic in San Pedro de Atacama and it may be preferable to arrange for these requirements to be available by enhancing this clinic, if necessary, rather than by providing a stand-alone facility.

On the 5000 m MMA site indoor work areas where difficult problem solving is required, such as the main control room, electronics and computer areas and engineering offices, will have an oxygen enriched atmosphere of 26 % oxygen, equivalent to an altitude of 3500 m (11500 ft). Enclosed work areas such as the antenna assembly building, the antenna receiver cabin, workshops, and the antenna transporter operator cabin will be designed so as to make oxygen enrichment possible if it turns out to be necessary. Outdoor workers will be supplied with portable oxygen if their tasks require it.

It is likely that a significant fraction of workers on the MMA site, at least on the first few days of their work week, will experience some symptoms of AMS. For those workers who require it acetazolamide will be provided to relieve these symptoms. Treatment for severe AMS, or cases where incipient HAPE or HACE is suspected, will be immediate descent by automobile to the OSB. As an emergency backup measure the site will be equipped with a portable hyperbaric bag.

Before workers begin work at 5000 m they should undergo a physical examination to identify any medical conditions, such as the list contained in section 2.9 above, which would make it inadvisable for them to work at this elevation. There should be a "two-man-rule"and a "two-vehicle-rule" in effect on the site at all times.

5. CONCLUSIONS

At 5000 m (16400 ft) the MMA site in Chile would be the highest continuously operated astronomical site in the world. At this altitude the medical and physiological effects of the reduced partial pressure of oxygen are significant but we do not believe that they are so serious as to make the site unfeasible. A key aspect of the site which makes it feasible is its easy access to low elevation. In a 1.25 hr drive on a good road one can reach a town at 2440 m (8000 ft) where a low elevation support base can be established. If a worker on the site begins to develop one of the serious high altitude illnesses he can immediately be taken to low elevation where the condition will quickly reverse. Additionally, the support base will be close enough to the site so that much of the work can be completed at low elevation with workers going to the site only when necessary. Indoor work areas on the site will have their atmospheres enriched with oxygen to a concentration of 26%, providing an equivalent working altitude of 3500 m (11500 ft). This working altitude is low enough so that the mental abilities of the workers in the buildings should not be noticeably impaired. It is expected that outdoor workers on the site will, in general, not require supplemental oxygen but, for particularly difficult outdoor tasks, portable oxygen will be available and its use will be encouraged. It can be expected that a significant fraction of workers on the site will experience some symptoms of Acute Mountain Sickness on the first day or two at altitude and effective medications are available to relieve these symptoms.

One of the reasons that we believe that it is feasible to build and operate the MMA at this high altitude is the successful operation of other high altitude facilities of similar complexity. The Mauna Kea Observatory at 4200 m is a proven successful operation. Whilst the altitude effects at 5000 m will be worse than those on Mauna Kea, the quantitative studies quoted above suggest that the problems will only be a few tens of percent worse, not a factor of several times worse. We believe that the use of oxygen enrichment for the MMA will make the MMA situation better than the Mauna Kea situation. A second example of a successful high altitude activity of comparable complexity to the MMA is provided by the high altitude mines in Chile, such as El Tambo and Collahuasi, some of which employ many hundreds of miners at altitudes up to 4600 m. These are modern facilities using the latest computer controlled technology requiring many of the same kinds of skills for their operation and maintenance as the MMA. These mines are now demonstrating the usefulness of oxygen enrichment.

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