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INTERNAL HEAT LOADS IN LUNARES ANALOGUE PLANETARY BASE – A CASE STUDY

This case study work focuses on recognising and quantifying internal heat sources in the first European analogue planetary base: the recently constructed Polish LUNARES habitat. The paper explains the necessity of conducting analogue space missions prior to an actual manned exploration of the Moon and Mars. Notions of internal heat loads and gains have been elaborated along with their significance for developing space building physics. This paper presents the results of thorough inspection of all internal heat sources, conducted by one of the authors during ICAres-1 Mars analogue mission aboard the LUNARES base. Three main sources of internal heat loads were identified and carefully studied; the habitat's electrical equipment, the crew body heat and their personal appliances. These heat loads were calculated and total internal heat load of the base was established and discussed. The results of this study may serve as a baseline for predicting internal heat loads aboard actual planetary bases.

Keywords: space building physics, internal heat gains, analogue space station, metabolic heat generation

1. Introduction

1.1. Analogue planetary stations

The development of manned space exploration requires an ability to test new technologies and human behavior in safe, controlled conditions, before an actual spaceflight takes place. Analogue planetary stations, also known as analogue planetary bases, analogue extraterrestrial bases or habitats are specially designed facilities, where selected aspects of long term human presence on extraterrestrial bodies may be simulated. In these facilities, technological solutions, procedures and guidelines for future Moon and Mars exploration are

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studied and improved. There are several analogue planetary bases in the world, and new ones are developed [1].

1.2. LUNARES

The first analogue habitat in Europe is LUNARES, located at former military airport in Piła, Poland. The habitat became operational in July 2017, beginning fourteen days long analogue Mars mission for 6 - personnel international crew.

LUNARES consists of a spacious central, domed hub called Atrium and eight adjacent modules, including a galley, dormitory, bathroom, storage, operations room, two laboratories and an airlock.

The secondary component of the LUNARES complex is a simulated lunar and martian terrain situated inside a reinforced aircraft hangar. The whole facility has been made completely lightproof to enable studies on human circadian rhythm and plant growth with artificial lighting.

1.3. Internal heat gains

In building physics, internal heat gains refer to heat emitted by all physical phenomena, activities and processes that release sensible and latent heat inside building envelope, but are not a part of building's heating system [2–5]. The most important internal heat sources are occupants body heat, electrical devices (lighting, appliances, office equipment), food preparation and domestic water heating and its consumption. Internal heat gains are expressed in unit energy, usually in MJ or kWh. Mean heat flux from internal heat sources is called internal heat load and is expressed in unit power [W] in terms of whole building or its section, or in unit power per unit floor surface [W/m^2] or in unit power per unit interior volume [W/m^3]. As a byproducts of mentioned phenomena, internal heat gains cannot be controlled without disrupting the function of a building. Internal heat gains increase the temperature of a building interior and may considerably contribute to building's thermal balance, especially in well thermal insulated objects [2,5,6].

1.4. Internal heat gains in extraterrestrial buildings

The settlements to be established on the surface of the Moon or Mars will initially serve as a scientific facilities, so it may be expected, that they will be equipped with a great variety of electrically powered devices. Additional heat will be produced by batteries and life support systems, such as water recovery and atmospheric control systems [7,8]. Moreover, due to extremely high costs of space transportation, these early extraterrestrial buildings would have highly limited volume and floor surface areas. These two factors suggest, that internal heat load per unit volume or unit surface in these buildings may be significantly higher than what we observe in residential or office buildings on Earth. Due to lack of atmosphere (Moon) or very low atmospheric pressure (Mars) both locations may be considered as highly insulative environments, where heat exchange between building interior and exterior is highly limited [7, 9–13]. In that situation, determination of internal heat gains becomes a matter of great importance.

An opportunity to study internal heat loads in these unusual buildings presented itself during ICAres-1 analogue mission onboard LUNARES habitat, where numerous scientific experiments were being performed. There were, among others: in situ material processing and utilization, plant growth and animal breeding, spare parts 3D printing, electromagnetic radiation measurements, group dynamics monitoring, continuous artificial lighting studies and extravehicular equipment testing. Although LUNARES lacks working life support system, it is well equipped with laboratory and everyday life devices, so studying its internal heat loads offered a reliable insight into future, full scale solutions.

The purpose of this paper was to identify and quantify all internal heat sources onboard LUNARES habitat in order to determine its total internal heat load.

2. Materials and Methods

2.1. Method

Assessment of internal heat load onboard LUNARES was based on:

- performing thorough inspection of all electrical devices inside the station i.e. learning their input power and daily use;
- conducting a survey among crew members, considering their biometrics, physical activities and electrical devices they used during the mission.

The study was performed in October 2017, during ICAres-1 Mars analogue mission. The corresponding author of this paper was one of ICAres-1 crew members and spent fourteen days onboard the station, acting as Structural material specialist and a PR officer. Thanks to this, the authors possessed a first-hand information about the station's inventory use and an actual, everyday mission schedules.

2.2. Questionnaire description

For the purpose of this paper, Information were gathered from crewmembers by specially prepared questionnaires, that addressed following issues:

- their mission assignments, sex, body weight and height;
- daily profile of their physical activities;
- electrical devices brought for personal use or research purposes;
- personal-use electrical devices, laboratory equipment, subsystems or installations that LUNARES lacks for long-term lunar mission (to be addressed in further studies).

We divided internal heat sources of the LUNARES base into three separate categories:

- base equipment;
- crew body heat;
- crew personal devices.

2.3. Heat loads from electrical devices

It was assumed, that all electric energy expended inside the base will be eventually transformed into heat, allowing it to be counted totally as internal heat loads. It was the case even with electrically heated domestic water, which was collected after each shower, dish washing etc. and used as grey water, allowing it to cool down to ambient temperature, releasing its excess heat into habitat interior.

Knowing the value of nominal power input and daily use of selected electrical devices one may calculate their contribution to mean internal heat load:

$$q_{el} = \sum_{i} \frac{P_i \times t_{mean.i}}{24} \ [W] \tag{1}$$

where: q_{el} is daily mean power demand of a group of electrical devices, i.e. its contribution to daily mean internal heat load, P_i is the mean power input of i- device [W], $t_{mean,i}$ is mean time of i- device daily use [h] and 24 is the number of hours per day

Heat loads from a base equipment and personal devices were calculated according to equation 1.

Electrical devices used only outside the habitat during extravehicular activities but recharged indoors, were accounted for according to equation 2.

$$q = \frac{P_{ch} \times t_{ch} \times (1 - \eta_{ch})}{24} \tag{2}$$

where P_{ch} is nominal power of the battery charger, t_{ch} is daily mean time of charging and η_{ch} is energy efficiency of battery charging

Power demand of group dynamics monitoring equipment SocSenSys was established using the experiment description [14,15]

2.4. Heat load from body heat

Calculation of waste body heat emitted to the surroundings by a person bases on their body surface area and on their instantaneous metabolic rate. The latter is expressed in MET units (Metabolic Equivalent of Task) which represents a ratio of the rate at which a person expends energy, while performing given physical activity compared to a reference value, equivalent to the energy expended when sitting idly. By the definition, the reference value $MET_0 = 58.2\ W/m^2$ [16].

Total body surface areas for the crew members were calculated using Du Bois formula:

$$BSA = 0{,}007184 \times m^{0{,}425} \times h^{0{,}725}\ [m^2] \tag{3}$$

where: BSA is body surface area [m^2], m is body mass [kg] and h is person's height [cm]

Basing on the data collected in the survey, mission profile of ICAres-1 and its daily schedules, daily physical activities of the crew were divided into three categories. The division and respective values of metabolic rates assumed for our calculations are presented in table 1.

Table 1. Metabolic rates assumed for the ICAres-1 crew

Activity symbol	Activity description	MET range	Average MET
PA-1	sleep, relax	0.8–1.0	0.90
PA-2	light intensity activities	1.6–2.2	1.90
PA-3	exercises and moderate activities	4.0–6.0	5.00

Daily mean heat load from the crew body heat was calculated as:

$$q_{bh} = \sum_{i,j} \frac{BSA_i \times MET_j \times t_{i,j}}{24}\ [W] \tag{4}$$

where BSA_i is body surface area [m^2] of i-person, MET_j is metabolic equivalent of task for j-activity [-], $t_{i,j}$ is daily mean time spent by i-person on j-activity [h], 24 is the number of hours per day because ambient temperature was not the same in every section of the base.

It was assumed, that due to proper adjustments of clothing for a specified activity and ambient temperature, crew members functioned in thermoneutral conditions i.e. they did not expend extra energy to maintain their body temperature. It is worth mentioning, that most EVAs were physically demanding operations, that have been considerably increasing subject's metabolic heat production. That increase lasted some time after returning to the habitat and presented short-time peak in body heat production inside the base. However, these contributions were judged to be negligible for the overall internal heat gain and were not addressed in the calculations. After three days of ICAres-1 mission, one of the crew members must have permanently left the experiment due to personal reasons. For the purpose of This paper, the situation was considered abnormal and unrepresentative, so metabolic heat loads were calculated here for the complete, six-personnel crew.

3. Results

3.1. Base equipment

Tables 2 to 10 presents heat loads from miscellaneous base equipment for each compartment of the base.

Table 2. Heat generation by the workshop equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
3d printer	700	12	350.00
Spectrometer	20	2	1.67
EVA radio battery charger	20	2	0.42
magnetometer battery charger	4	0.14	0.002
soldering iron	100	0.083	0.35
Fan (2x)	20	24	20.00
lighting (5x 20W LED lamps)	100	4	16.67
Laptop	60	12	30.00
interior monitoring camera 2x	10	24	10.00
		in total:	429.10

Table 3. Heat generation by the Storage equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
lighting (5x 20W LED lamps)	100	4	16.67
Fan (2x)	20	24	20.00
interior monitoring camera 1x	5	24	5.00
		in total:	41.67

Table 4. Heat generation by the Galley equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
fluorescent lamp	144	5	30.00
interior monitoring camera 1x	5	24	5.00
microwave	800	0.75	25.00
induction oven	2000	0.25	20.83
projector	60	0.5	1.25
domestic water electric heater	2200	0.033	3.03
Fan (2x)	20	24	20.00
router	30	24	30.00
		in total:	135.11

Table 5. Heat generation by the Dormitory equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
fluorescent lamp	144	2	12.00
Fan (2x)	20	24	20.00
interior monitoring camera 1x	5	24	5.00
		in total:	37.00

Table 6. Heat generation by the Operations room equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
fluorescent lamp	144	6	36.00
Fan (2x)	20	24	20.00
interior monitoring camera 1x	5	24	5.00
laser printer	800	0.03	1.11
SocSenSys devices	20	24.00	20.00
modem	20	24	20.00
		in total:	102.11

Table 7. Heat generation by the Biolab equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
room lighting (3x 20W LED lamps)	60	4	10.00
air compressor	3.5	24	3.50
plant lighting (2x16W LED lamps)	32	24	32.00
plant lighting (3x32W LED lamps)	96	24	96.00
plant lighting (1x10W LED lamps)	10	24	10.00
microcentrifuge (4x)	12	24	12.00
Fan (1x)	10	24	10.00
interior monitoring camera 1x	5	24	5.00
		in total:	178.50

Table 8. Heat generation by the Bathroom equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
fluorescent lamp	144	2	12.00
domestic water heater	1500	3	187.50
		in total:	199.50

Table 9. Heat generation by the Atrium equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
LCD status monitor	150	24	150.00
interior monitoring camera 1x	5	24	5.00
air dryer	1200	24	1200.00
artificial daylight LEDs	150	24	150.00
airlock status lamps	48	24	48.00
		in total:	1553.00

Table 10. Heat generation by the Airlock equipment

Device	Nominal power input [W]	Daily use [h]	Daily mean heat generation [W]
interior monitoring camera 1x	5	24	5.00
decontamination UV lamps	6	0.5	0.13
		in total:	5.13

Table 11 summarises the most important results from tables 2 to 10 and additionally shows the values recalculated per unit surface and per unit volume. TRC stands for temperature regulated compartment. This position was introduced, because the airlock was not a TRC. Further considerations involves TRCs only.

Table 11. Heat loads from the habitat equipment for separate compartments

Compartment	Mean heat load [W]	Floor surface area [m^2]	Interior volume [m^3]	Mean heat load per unit surface [W/m^2]	Mean heat load per unit volume [W/m^3]
analitical laboratory	429.10	17.20	28.80	24.95	14.90
storage	41.67	13.00	34.40	3.21	1.21
galley	135.11	13.00	30.40	10.39	4.44
dormitory	37.00	19.70	49.20	1.88	0.75
operations room	102.11	19.70	49.20	5.18	2.08
biolab	178.50	8.00	18.30	22.31	9.75
bathroom	199.50	8.00	18.30	24.94	10.90
atrium	1553.00	37.20	150.00	41.75	10.35
airlock	5.13	15.50	34.00	0.33	0.15
total	2681.11	151.30	412.60	17.72	6.50
total TRC	2675.99	135.80	378.60	19.71	7.07

The total heat load from the base equipment equals almost 2.676 W and gives heat load per unit surface as high as 19.71 W/m^2. This value alone constitutes significantly higher heat load, than total internal heat load in residential buildings [2,5,17] or electric devices heat generation in modern, well equipped offices [18].

Considerable differences in heat loads are to be observed between individual compartments. These results reflect the actual thermal comfort issues observed during the mission, when some compartments were being easily overheated, while other ones required increased heating to maintain desired temperature. Such differences in heat loads between compartments require highly effective interior air circulation system to enable proper heat distribution.

3.2. Body heat

Table 12. Presents daily mean body heat production by ICAres-1 crew. The time of daily activities does not sum up to 24h/day due to extravehicular activities performed by the crew.

Table 12. Daily crew activities and body heat generation

Crew member	Body surface area [m^2]	Daily mean time spent at physical activities [h]			Mean waste heat generation [W]
		PA-1	PA-2	PA-3	
A	1.65	8.00	14.00	1.25	159.86
B	1.63	8.00	15.00	0.50	150.79
C	1.89	8.00	15.00	0.50	174.83
D	1.86	8.50	13.50	1.25	177.99
E	1.88	9.00	13.00	1.25	177.97
F	2.25	7.00	13.00	3.25	257.56
				in total:	1099.00

This group of internal heat sources provides a substantial contribution to the total internal heat load. In comparison with terrestrial houses or offices, the studied base is rather moderately occupied, offering 22.6 m^2/person, but is almost constantly fully staffed, what is not the case in most of the buildings on earth. Moreover, noticeable amount of time was being spent by the crew on physical exercises, what elevated average metabolic heat generation aboard the habitat. During the ICAres-1 mission, daily mean metabolic heat load per unit floor surface was 8.09 W/m^2. This situates the result between metabolic heat loads for residential buildings and for offices during working hours [2,18]. However, when daily mean metabolic heat loads per unit floor surface are compared, LUNARES presents noticeably higher value, than either houses or offices.

3.3. Personal devices

The list of crew personal devices and their contributions to internal heat loads are presented in table 13.

All of these devices have either low power demands or were usually rarely used. The total mean heat load from this group of internal heat sources (almost 113 W) is relatively low and have no significant effect on total internal heat load in the base.

Table 13. Heat generation by personal devices

Device	Nominal power input [W]	Mean daily use [h]	Daily mean heat generation [W]
laptop 1	65.00	9.00	24.38
Camera	10.00	2.00	0.83
E-book readere	5.00	0.25	0.05
laptop 2	80.00	6.00	20.00
Camera	10.00	0.50	0.21
smartphone	2.00	0.20	0.02
IR camera	10.00	0.25	0.10
laptop 3	60.00	2.00	5.00
smartphone	2.00	1.00	0.08
laptop 4	80.00	10.00	33.33
mp3 player	5.00	2.00	0.42
laptop 5	65.00	8.00	21.67
laptop 6	70.00	2.00	5.83
smartphone	5.00	5.00	1.04
		in total:	112.96

3.4. Total internal heat load

The table 14. Compares heat loads for all three internal heat sources.

Table 14. Comparison of internal heat loads aboard the LUNARES habitat heat source

Physical quantity	Habitat equipment	Body heat	Personal devices	Total
internal heat load[W]	2675.99	1099.00	112.96	3774.98
internal heat load per unit surface [W/m^2]	19.71	8.09	0.83	27.80
internal heat load per unit volume [W/m^3]	7.07	2.90	0.30	9.97

As suspected the total internal heat load aboard the analogue planetary base LUNARES during ICAres-1 mission went far beyond the values observed in residential buildings and slightly exceeded the value for well-developed offices. In highly insulative environment that value of internal heat loads will require highly efficient thermal control system to maintain interior thermal comfort.

3.5. Additional remarks

It is to be observed, that the LUNARES habitat is not equipped with an actual life support system, interplanetary communication, nor with energy storage solution, that would be mandatory for an actual, solar powered lunar or martian base [7,19]. It is to be suspected, that waste heat generated by these systems will considerably increase station's total internal heat load. Another issue to be addressed in the future is the way we compare internal heat loads. The well-established practice is to calculate heat loads per unit floor surface area. This is a correct approach as long as interior heights of compared buildings remain similar. If, however, living in partial lunar or martian gravity would force significant increase in extraterrestrial buildings' interior heights, using unit volume instead unit surface may turn out to be more suitable basis for comparing internal heat loads.

4. Conclusions

In this paper internal heat sources aboard the LUNARES, an analogue planetary base have been identified and quantified. The calculated total, daily mean internal heat load 27.8 W/m^2 is considerably higher than the value for residential buildings and slightly higher than for well-developed offices. Internal heat loads in an actual extraterrestrial base would be still much higher than the calculated value due to presence of life support, interplanetary communication and energy storage systems, which were absent in the analysed building. While this paper provides reliable assessment of a heat load from appliances and laboratory equipment, total internal heat load of an actual planetary base are to be subject of further studies.

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