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# Range, Energy, Heat of Motion in the Modified NBC, Anti-*g*, Tank Suit

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**The modified nuclear, biologic pathogen, chemical (NBC), anti-*g*, anthropomorphic tank suit (ATS 2), was designed and modified by one of the authors, A.N. de G. The ATS 2 provided a protective liner of water around, but not in contact with, the subject to the neck. For three subjects in the ATS 2, range of motion was lost in 30 of 32 tests by an average of 39% dry and 40% wet, $p < 0.001$. For work rates from 49 to 151 W, all blood pressures were significantly elevated, $p < 0.05$, but no other significant differences were found. The factors dry and wet, for heart rate were 1.2, 1.3; for systolic blood pressure 1.2, 1.4; for diastolic blood pressure 1.1, 1.3; for estimated mean blood pressure 1.1, 1.3; for ventilation 1.7, 2.0 and for energy of motion 1.40, 1.53. The factor 1.53 was an underestimation because of a suppressed maximal oxygen consumption. Special joints, pressure breathing and water cooling seemed desirable for future suits. From centrifuge tests, maximum *g* tolerance remained unknown and the question of the necessity for "*g*-inhibiter" systems in high performance aircraft remained unanswered.**

## Introduction

NUCLEAR, biologic pathogen, or chemical (NBC) agents introduced into the mission environment threaten safety and limit human performance. The NBC suit is a counter measure to these agents. In previous NBC suits, ranges of motion were diminished, response times increased, fine eye-hand coordination was degraded, the metabolic costs of movements were increased and heat accumulated.[3,7,10,23] These consequences limited mission performance and threatened safety. The task of this study, done under contract to Douglas Aircraft Company, was to test a modified NBC anthropomorphic tank suit (ATS 2), designed and modified by one of the authors, A. N. de G. The ATS 2 provided a protective liner of water around the subject to the neck. The tests determined how much mobility and efficiency of movement were lost from the stiffness of the suit around the joints and how much thermoregulation was lost consequent to the impermeability of the suit.

The ATS 2 had a double liner with the water between the two liners and therefore not in contact with the skin. ATS 1, fabricated and tested in 1988, had a single liner, resembling a dry diving suit, with the water contained between the liner and the skin. A strong outer garment was laced over the liner(s) to prevent the ballooning of the liner(s) from the water's pressure. These suits provided protection against various NBC environments because a fluid barrier surrounded the entire body, except for the head, and the fluid could be optimized in future studies to give protection against one or several defined environments. For this study, the only fluid used was water.

For ATS 2, the null hypothesis was that there would be found no significant differences among the unclad, clad dry (no water in the liner) and clad wet (with water in the liner) conditions for mobility, thermoregulation, energy cost and cardiorespiratory responses to moderate work rates.

Except for the report on ATS 1, the authors were unable to find reports on the energy requirements for work in NBC or anti-*g* suits. In the ATS 1, the metabolic rate dry was 1.48 times higher than unclad and wet 1.73 times higher. This was compared to 1.66 to 3.96, respectively, for space suits.[10]

Except for the report on ATS 1, for a standardized task independent of body weight, like bicycle ergometry, the authors were unable to find for NBC or anti-*g* or space suits cardiorespiratory responses like heart rate, blood pressures, and expired volume. In the ATS 1 in the donned conditions, all of these responses were elevated. The factors dry and wet, respectively, for heart rate were 1.2, 1.3; for systolic blood pressure 1.3, 1.4; for diastolic blood pressure 1.3, 1.4; for estimated mean blood pressure 1.3, 1.4; and for ventilation 1.3, 1.8.[10] The authors also were unable to find for any of the other suits any documentation on the losses of range of motion or any effects of being immersed to the neck as in a tank suit. In the ATS 1, range of motion was lost in 29 of 32 tests by an average of 25% dry and 30% wet. During physical activity, unexpectedly high blood pressures and core temperatures were observed, with a thermal "afterrise" phenomenon that may have been physiologically analogous to the "afterdrop" found during rewarming after hypothermia.[1,4,6,8,10,14,20–22,24] This gave indications for redesign and warning for future studies.[10] For anti-*g* protection, the ATS 1 showed promise for the removal of "*g*-inhibiter" systems in high performance aircraft. One subject was tested in a centrifuge in a standard, seated, relaxed posture, without any voluntary straining maneuvers and tolerated, without vision narrowing or other untoward effects, $+3.0\,gz$ in the ATS 1 dry and $+7.0\,gz$ for 1.5 min, the limit of the centrifuge, in the ATS 1 wet. Maximum *g* tolerance in the ATS 1 wet remained unknown because the centrifuge

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failed mechanically.[10] Therefore, another purpose of this study was to apply the protocols developed for ATS 1 and to report these data on the same sample of men in the redesigned suit, ATS 2.

## Methods

The subjects were three investigators for this study who gave their informed consent. The fourth investigator, a physician, took medical responsibility. Determinations were obtained on the three subjects unclad, as the standard, and were compared to the determinations in the ATS 2 without water in the liner (dry) then with water in the liner (wet). The ATS 2 results were reported as multiples or percentages of this unclad standard.

Range of motion was determined with a goniometer in a standardized protocol of 32 tests modified from the International SFTR Method by the American Academy of Orthopedic Surgeons.[5] There were four tests for the head and neck, three for the thoracic and lumbar spine, eight for the leg, six for the hand, and eleven for the arm. The extreme positions of the defined motion, in degrees, were obtained with the goniometer, and the difference gave the range of motion. For the ATS 2 dry and wet, these ranges of motion were normalized to the unclad determinations.

Energy requirements were determined by obtaining the oxygen consumption in a steady state on a Monark bicycle ergometer, equipped with a pedal counter and speedometer, at a cycling rate of 50 rpm. Oxygen consumption was determined directly during the last minute of exercise with an open system, using a Collins 120-l spirometer and a Haldane-Henderson gas analyzer and was reported STPD, standard temperature (0°C) pressure (760 mm Hg) dry (0 mm Hg water vapor pressure).[9,11] To obtain steady states, determinations were made for 6 min at 50 and 100 W and for 5 min at 150 W.[2,9] The means of the last minute of exercise were used for comparisons. Blood pressures were obtained phonoarteriographically from an electronically recorded sphygmomanometric method intra-arterially validated for rest, exercise, and the rest after exercise.[13] Mean blood pressure was estimated as the diastolic blood pressure plus one-third the pulse pressure. Heart rates were the mean of 10 R-to-R determinations obtained from the brachial pulse of the blood pressure tracings from a Statham SM1051 recorder. Expired volume was obtained from the Collins 120-l spirometer and was reported BTPS, body temperature (37°C), pressure (760 mm Hg) and saturated (47 mm Hg water vapor pressure).

Rectal temperature in degrees C was obtained with a thermistor probe inserted 20 cm into the rectum[14–19] and a Yellow Springs Instrument Tele-Thermometer meter. Determinations were made for each minute of exercise and rest unclad, in the ATS 2 dry and in the ATS 2 wet. Temperature determinations also were made on the water used to fill the liner. Humidity was determined with a sling psychrometer and barometric pressure was obtained from an airport weather station within 18 km of the laboratory.

The unclad determinations were made in one session and the clad, dry then wet, determinations were made in a second session on a separate day. If a steady state was obtainable dry, then the assumption was made that the subsequent wet determinations were unaffected as is the case in discontinuous and continuous exercise tests.[2,9,11,12] Time in the suit and the quantity as well as the temperature of the water put in the liner were recorded. Body and suit weights were obtained on a balance with a range of 153 kg that was sensitive and accurate to 5 g.

All three subjects completed all of the range of motion and exercise protocols unclad, clad dry, and clad wet (Figs. 1–6). Only subject 2 was tested for maximum metabolic rate unclad and compared to clad wet (Fig. 7).

The differences amongst the means unclad, in the ATS 2 dry and in the ATS 2 wet were tested with an analysis of variance (df = 2, 2) and if significant, $p < 0.05$, then the post-hoc Tukey test was used to identify statistically significant specific differences at $p < 0.05$.

## Results

The mean (±standard deviation) age of the subjects was 44.8 ± 15.1 yr, height was 185.1 ± 2.9 cm, and body weight was 82.2 ± 4.8 kg. All three subjects were in good physical condition. The lowest peak oxygen consumption of 3.5 l/min (45 ml/min·kg) and the highest body fat content of 13% were for subject 2. The dry ATS 2 weighed 7.19 kg, and the water in the liner varied from 12.14 to 24.40 kg for a total weight of 19.33 to 31.59 kg. Time in the ATS 2 averaged 217 ± 17 min per session.

In the ATS 2, there was a loss in range of motion in 30 of the 32 movements tested, 19 of which were statistically significant: foot extension (test 2), foreleg flexion (test 3), femur flexion (test 4), femur extension (test 5), head extension (test 10), spine extension (test 14), spine abduction (test 15), hand flexion (test 16), hand extension (test 17), hand pronation (test 21), forearm flexion (test 22), vertical humeral outward rotation (test 24), horizontal humeral outward rotation (test 26), horizontal humeral abduction (test 27), and adduction (test 28), humeral flexion (test 29), and extension (test 30), humeral abduction (test 31), and humeral adduction (test 32). In percent, the mean (±SD) losses dry and wet, respectively, were 42.8 ± 7.2 and 40.8 ± 3.3 for the legs ($p$ = 0.002), 11.3 ± 18.5 and 12.5 ± 8.1 for the head ($p$ = 0.36), 39.6 ± 9.5 and 34.0 ± 10.1 for the thoracic and lumbar spine ($p$ <

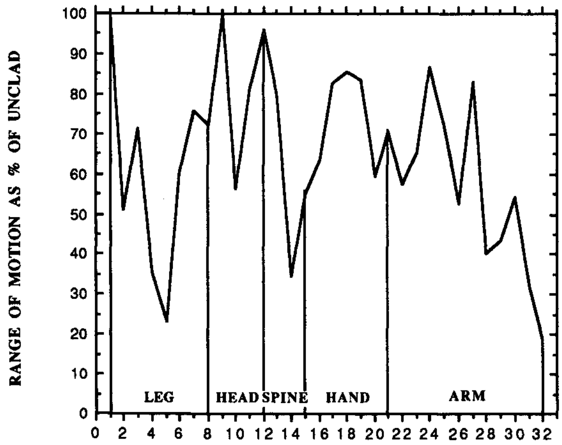


**Fig. 1 Range of motion in the ATS 2 (dry, i.e., without water in the liner) for the three subjects normalized to range of motion unclad. The abscissor represents the standardized protocol of 32 tests (see Methods and Ref. 5).**

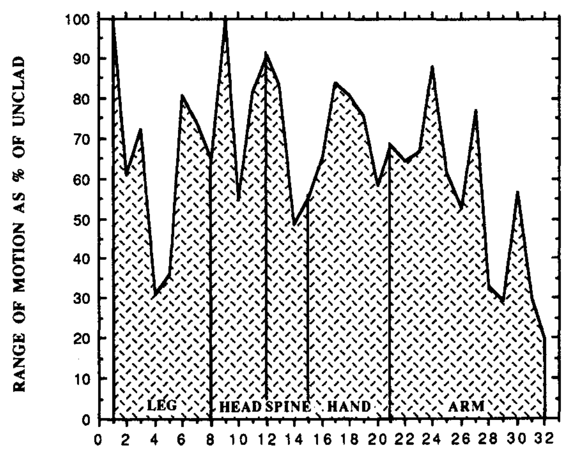


**Fig. 2 Range of motion in the ATS 2 (wet, i.e., with 14.4 ± 2.4 l of water in the liner), for the three subjects normalized to range of motion unclad. The abscissor represents the standardized protocol of 32 tests (see Methods and Ref. 5).**

0.004), 28.2 ± 8.6 and 30.0 ± 3.5 for the hand ($p = 0.008$), 47.4 ± 10.7 and 50.6 ± 8.4 for the arm ($p < 0.001$) and overall 38.7 ± 9.8 and 39.9 ± 5.7 ($p < 0.001$), as may be seen in greater detail in Figs. 1 and 2. The water in the liner was 14.4 ± 2.4 liters.

For the steady-state work rates from 49 to 151 W, normalizing the response for each watt of work rate, the ATS 2 dry required a metabolic rate 1.40 times higher than unclad, and the ATS 2 wet 1.53 times higher. Subject 2 was at maximum metabolic rate at 95 and 123 W in the ATS 2 wet, therefore the 1.53 underestimated the factor wet. Unclad, dry, and wet were not significantly different from each other at each work rate. The equations indicated increased intercepts, with high accuracy of fit to the data, $R^2 = 0.996$ to 1.000, as may be seen in Fig. 3. The heart rate responses were higher by factors of 1.2 dry and 1.3 wet and those for ventilation 1.7 and 2.0, respectively, as may be seen in Fig. 4. For heart rate and ventilation, the differences were not statistically significant. The factors for the systolic blood pressures were 1.2 and 1.4, for the diastolic and estimated mean 1.1 and 1.3, respectively, as may be seen in Fig. 5. For all of the blood pressures, the differences were statistically significant, $p < 0.05$. The factors for rectal temperature were 1.01 dry and 1.03 wet as may be seen in Fig. 6. The differences were not statistically significant. Total time in the ATS 2 averaged 217 ± 17 min. The liner water was 20.78 ± 2.01 liters at a temperature of 22.7 ± 1.9°C. The room temperature averaged 20.2 ± 1.1°C with 45.3 ± 12.8% humidity.

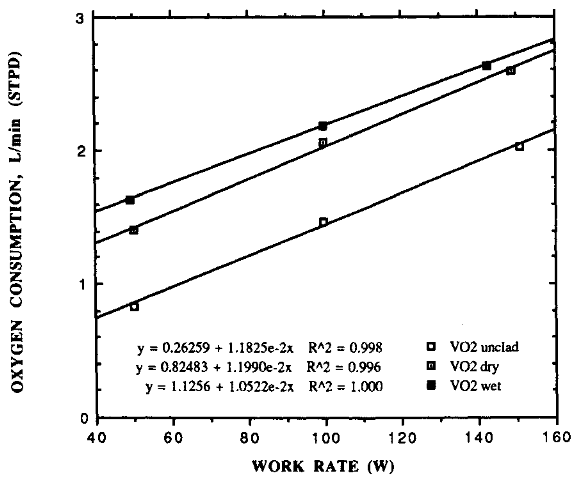


**Fig. 3 Steady-state energy cost of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS 2 (dry) and in the ATS 2 (wet, i.e., with 20.78 ± 2.01 l of water in the liner) for the three subjects.**

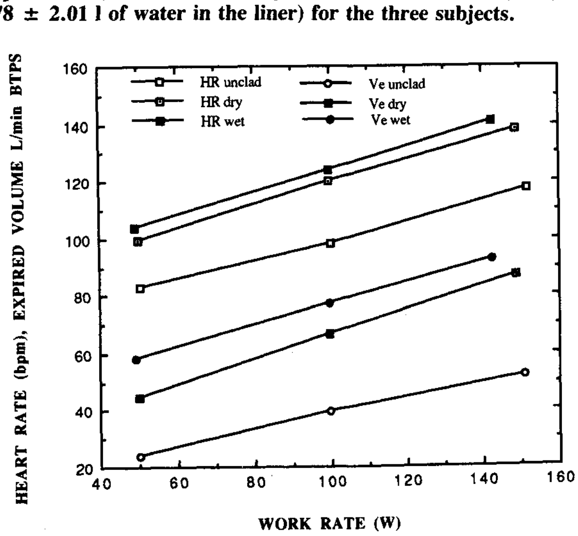


**Fig. 4 Steady-state heart rate (HR) and expired volume (Ve) of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS 2 (dry) and in the ATS 2 (wet, i.e., with 20.78 ± 2.01 l of water in the liner) for the three subjects.**

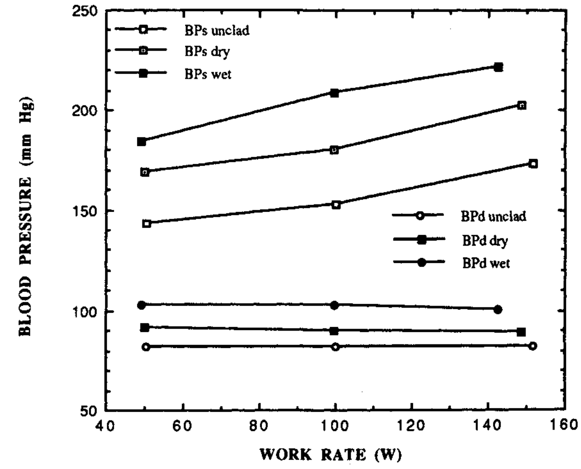


**Fig. 5 Steady-state phonoarteriographic systolic (BPs) and diastolic (BPd) blood pressures of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS 2 (dry) and in the ATS 2 (wet, i.e., with 20.78 ± 2.01 l of water in the liner) for the three subjects.**

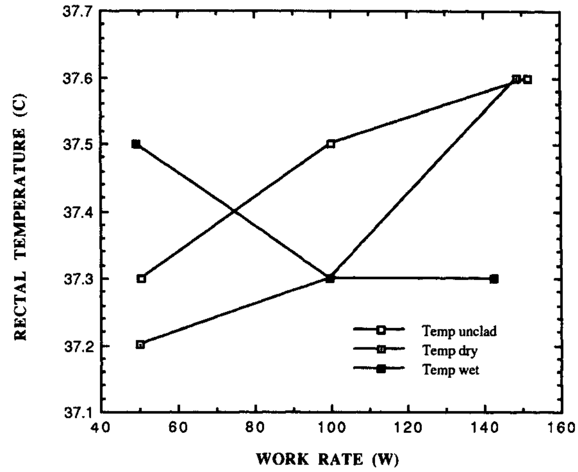


**Fig. 6 Steady-state rectal temperature of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS 2 (dry) and in the ATS 2 (wet, i.e., with 20.78 ± 2.01 l of water in the liner) for the three subjects.**

## Discussion

Most of the loss in range of motion, 39%, was caused by the stiffness of the ATS 2. The addition of the water to the liner resulted in a modest additional overall 1% additional loss in mobility as may be seen in Figs. 1 and 2. Similarly, most of the increased metabolic cost of motion may be attributed to the stiffness of the ATS 2 rather than to the water in the lining. The stiffness of the suit is represented in the metabolic rate equation by an increase in the intercept of 314% and by an increase in the slope of 1%. The average additional energy cost from the suit for the three work rates was 40% and from the water an additional 13% as may be seen in Fig. 3. If not limited by other factors, this suggested that the unclad work rate that elicited the maximal metabolic rate of physical activity would be attenuated clad dry and clad wet as indicated by the respective equations. Furthermore, there was evidence that the suit wet was attenuating the maximal metabolic rate attainable and this was the reason for the diminished slope wet seen in Fig. 3. Figure 7 shows a maximum oxygen consumption test unclad and clad wet for subject 2. This subject required ventilations greater than 100 l/min to achieve a maximal metabolic rate unclad, but the ATS 2 wet apparently did not permit ventilations above 100 l/min. At 95 W, the ATS 2 wet also apparently brought the subject to the

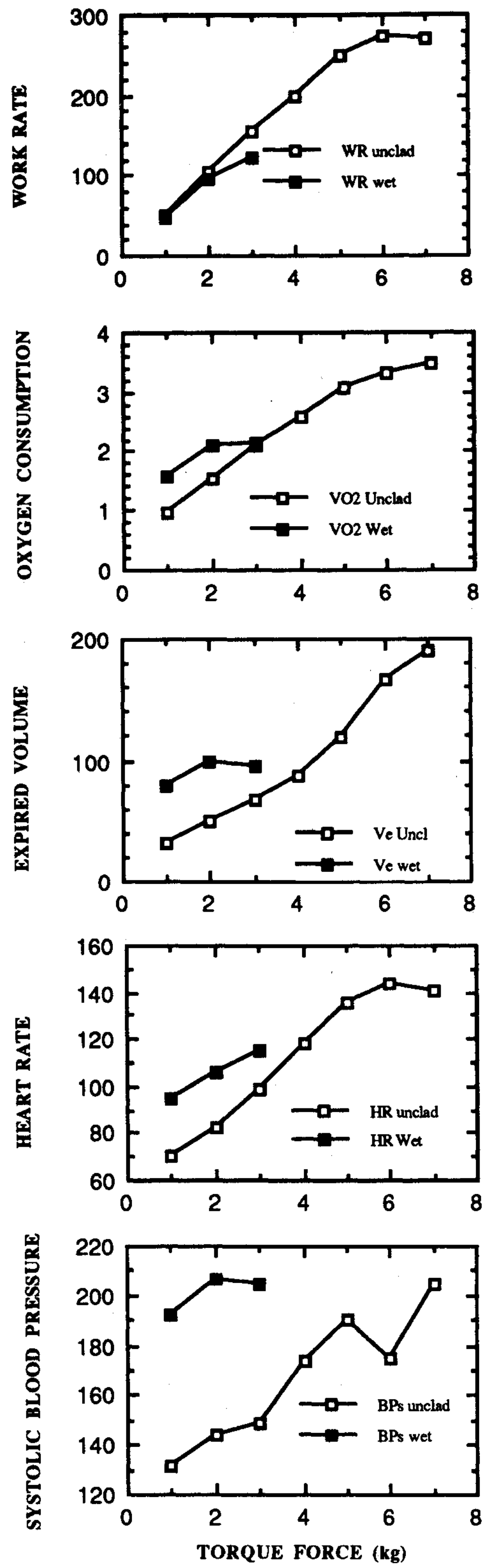


**Fig. 7 Torque force (kg) vs work rate (W), oxygen consumption (l/min STPD), expired volume (l/min BTPS), heart rate (beats/min), and phonoarteriographic systolic blood pressure (mm Hg) unclad and in ATS 2 wet for subject 2. Note the plateaux in oxygen consumption, expired volume, and systolic blood pressure in the ATS 2 wet.**

limit of his systolic blood pressure. These cardiorespiratory limitations were associated with a suppression of the maximum metabolic rate from 3.5 l/min unclad to 2.1 l/min in the ATS 2 wet, as may be seen in Fig. 7. The energy factor wet of 1.53 therefore was an underestimation.

A comparison indicated greater losses in range of motion dry and wet in ATS 2 than in ATS 1. ATS 2 weighed more, held more water, and suppressed the maximal metabolic rate of Subject 2 from 3.5 to 2.1 l/min as may be seen in Table 1.

**Table 1 ATS 1 and ATS 2 compared**

| Datum | ATS 1 Dry | ATS 1 Wet | ATS 2 Dry | ATS 2 Wet |
|---|---|---|---|---|
| Range of motion (%) | | | | |
| Leg | 71.9 | 59.8 | 57.2 | 59.2 |
| Head | 91.9 | 84.6 | 88.7 | 87.5 |
| Spine | 81.4 | 81.7 | 60.4 | 66.0 |
| Hand | 82.8 | 80.5 | 71.8 | 70.0 |
| Arm | 64.4 | 63.0 | 52.6 | 49.4 |
| Mean | 74.7 | 69.9 | 61.3 | 60.1 |
| SD | 17.5 | 19.6 | 21.8 | 21.1 |
| Liner water (liters) | — | 12.4 | — | 14.4 |
| Cardiorespiratory factors | | | | |
| Heart rate | 1.2 | 1.3 | 1.2 | 1.3 |
| Systolic blood pressure | 1.3 | 1.4 | 1.2 | 1.4 |
| Diastolic blood pressure | 1.3 | 1.4 | 1.1 | 1.3 |
| Mean blood pressure | 1.3 | 1.4 | 1.1 | 1.3 |
| Expired volume | 1.3 | 1.8 | 1.7 | 2.0 |
| Energy cost | 1.48 | 1.73 | 1.40 | 1.53* |
| Liner water | | | | |
| Liters | — | 9.85 | — | 20.78 |
| Temperature | — | 23.7 | — | 22.7 |
| Ambient | | | | |
| Temperature | 25.5 | 25.5 | 20.2 | 20.2 |
| Humidity | 61.7 | 61.7 | 45.3 | 45.3 |
| Barometer | 760.8 | 760.8 | 763.6 | 763.6 |

*Note: Subject 2 was at a suppressed maximum metabolic rate at 95 and 123 W. Therefore, 1.53 was an underestimation.

Tasks and thermoregulation for pilots probably would not suffer significant degradation consequent to wearing ATS 1 or 2. Tasks for transport crewman might suffer degradation if the metabolic rate requirements were more than moderate or if the environment were hot. In those cases, the design additions of choice for the ATS 1 and 2 were pressure breathing, cooling of the liner fluid, and special joint designs to increase mobility and reduce the energy cost of movement. With water in the liner, protection was at least $+7.0\ g_z$ for 1.5 min in ATS 1, the limit of the centrifuge before it failed. Testing in a centrifuge with a capacity greater than $+7.0\ g_z$ for 1.5 min was not available. Therefore, the question of whether or not ATS 1 or 2 permitted removal of "$g$-inhibiter" systems from high performance aircraft remained unanswered.

## Summary and Conclusions

The purpose of the study was to test range of motion, energy required to move, cardiorespiratory responses, and heat accumulation of a modified anti-$g$, NBC water-lined anthropomorphic tank suit (ATS 2) designed and modified by A. N. de G. Three subjects were tested in the ATS 2 without (dry) and with (wet) water in the liner. The null hypothesis was that there would be found no significant differences among the unclad, dry, and wet conditions for mobility, thermoregulation, energy cost, and cardiorespiratory responses to moderate work rates. The results indicated a loss in range of motion in 30 of 32 tests by an average 39% dry and 40% wet, $p < 0.001$. For steady-state work rates from 49 to 151 W, the ATS 2 dry required a metabolic rate 1.40 times higher than unclad, and the ATS 2 wet 1.53 times higher, with evidence that the 1.53 factor was an underestimation. These increases in metabolic rate also were reflected in higher heart rates, blood pressures, ventilations, and rectal temperatures, with only the blood pressure differences statistically significant. Therefore, the hypothesis was rejected. Special joints, pressure breathing, and cooling of the liner fluid were considered desirable future design additions. The question of whether or not ATS 1 or 2 permitted removal of "$g$-inhibiter" systems from high performance aircraft remained unanswered.

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