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GREAT BARRIER REEF WONDERLAND AQUARIUM TEMPERATURE VARIATION

Prepared for the

Great Barrier Reef Marine Park Authority

Report No. 1033

December 1986

DEPARTMENT OF CIVIL AND SYSTEMS
ENGINEERING

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2 January 1987

Mr G. Kelleher,
Chairman,
Great Barrier Reef
Marine Park Authority,
75 Denham Street,
TOWNSVILLE. QLD. 4810

Dear Graeme,

The attached report has been prepared for the Great Barrier Reef Marine Park Authority by Dr M.K. James. It results from a theoretical study, commissioned by the Authority, of possible temperature variation in the main tank of the Great Barrier Reef Wonderland Aquarium.

Recommendations are made concerning further study of the problem, as well as a possible temperature control mechanism.

The co-operation and assistance of Mr I.D. Burston, Mr G. Just and Dr M. Jones of the Authority, are gratefully acknowledged.

Yours sincerely,

Professor K.P. Stark
Head, Department of Civil
and Systems Engineering.

Enc.

2 copies received
1 to 1 Burston

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TOWNSVILLE

STUDY REPORT

GREAT BARRIER REEF WONDERLAND
AQUARIUM TEMPERATURE VARIATION

PREPARED FOR

THE GREAT BARRIER REEF MARINE PARK AUTHORITY

BY

DR. M.K. JAMES

IN CONSULTATION WITH

DR. S. SRINIVASA MURTHY

DEPARTMENT OF CIVIL AND SYSTEMS ENGINEERING
JAMES COOK UNIVERSITY OF NORTH QUEENSLAND

SEPTEMBER-DECEMBER 1986

1. INTRODUCTION

This study was commissioned by the Great Barrier Reef Marine Park Authority, with the objective of estimating possible temperature variations in the main reef tank of the Great Barrier Reef Wonderland aquarium.

The study brief indicated tolerable lower and upper temperature limits of $19^{o}C$ and $31^{o}C$, with a maximum daily range of $2^{o}C$.

In the event that temperature variations appeared likely to go beyond these limits, suggestions regarding temperature control mechanisms were also requested.

1.1 Approach Adopted

Preliminary investigations revealed a lack of published information on problems of this nature.

Local government authorities in the Townsville area evidently make occasional recordings of swimming pool and reservoir temperatures. These data are quite inadequate for the present purpose.

A literature search (solar energy applications; general engineering; aquaculture) showed that the closest approximation to the present problem is to be found in experimental and theoretical work on solar ponds (e.g. Rabl and Nielsen, 1975; Shah et al, 1981; Hull, 1985).

However in those systems, the fluid is deliberately maintained in a stratified condition, in contrast to the well-mixed state of the aquarium. Results from such work are therefore not directly applicable here. However some useful insights, and data, concerning the processes involved were gained from the investigation.

The lack of applicable experimental data meant that it was necessary to make a theoretical analysis of temperature variations, by considering heat transfer between the aquarium and its environment. Such heat transfer is dependent on solar radiation and meteorological conditions (wind speed, air temperature and relative humidity), which vary considerably from hour to hour.

An approach based on mathematical modelling and simulation was adopted. Temperature variation with time is modelled by the relationship:

$$\Delta Q = MS\Delta T$$

where ΔQ = net energy input,
M = total mass of fluid,
S = specific heat of fluid,
ΔT = temperature change.

A continuous-time simulation of temperature variation was developed, based on the above relationship. The net energy input is computed at each time step by computing energy gains and losses via the heat transfer processes included in the model. The model then produces hourly values of simulated water temperature in the aquarium.

Simulation runs have been carried out using synthetic solar radiation data, and historical time series of meteorological data for the years 1960-69. Short term runs (for the two years 1975-76) were also done, using historical radiation data. (The historical radiation data for 1975-76 were used to build a model to provide the synthetic radiation data needed for the longer runs.)

2. SUMMARY

2.1 A simplified model has been developed and used to simulate heat transfers to and from the main reef tank. The model produces, as output, hourly values of water temperature in the tank.

2.2 Results from ten years of simulated time have been analysed to give frequency distributions of daily maxima, minima and ranges, as well as runs of consecutive days on which tolerable limits are exceeded.

2.3 The likelihood of excessively high temperatures depends very much on the assumptions made concerning:
(a) the proportion of incident solar radiation absorbed;
(b) the effect of wind blockage by surrounding structures. Under the most favourable assumptions, the limiting temperature of 31°C is unlikely to be exceeded. However under the least favourable assumptions, this limit could be exceeded on about 7% of days, with temperatures in excess of 33°C being occasionally recorded.

Under all but the most favourable assumptions, high temperatures (greater than 31°C) could be expected to persist for extended periods ranging from a few days, up to almost two months, for the most extreme assumptions. These extended periods usually coincide with persistently calm weather in summer.

2.4 The model has been used to investigate the potential value of shading the water surface (using shade cloth, for example). These experiments indicate a very beneficial effect, even under the most extreme assumptions.

2.5 The following recommendations are made:

(i) As soon as practicable, continuous recordings of water temperatures in the aquarium should be made, to develop a set of data which could be used to calibrate the model. Measurements should be taken at three depths: near the water surface, close to the bottom, and at an intermediate depth.

If the calibration is successful, a more reliable assessment of the risks of temperature extremes could then be made, so that planning for the 1987-88 summer could be carried out.

(ii) The feasibility of erecting shade cloth over the aquarium surface should be investigated.

3. TEMPERATURE SIMULATION MODEL

3.1 Assumptions

The system to be modelled is represented schematically in Figure 1.

Water is circulated continuously through the algal scrubber trays, with the full main tank volume being turned over once every 24 hours. Each tray is irradiated at night for 6 hours. A diurnal tidal cycle is simulated by pumping to and from the tidal holding tank.

A wavemaking machine operates at one end of the tank, and a simulated reef structure is centrally located and occupies a significant proportion of the tank volume. A low structure housing an observation area, runs along the N.E. side of the tank.

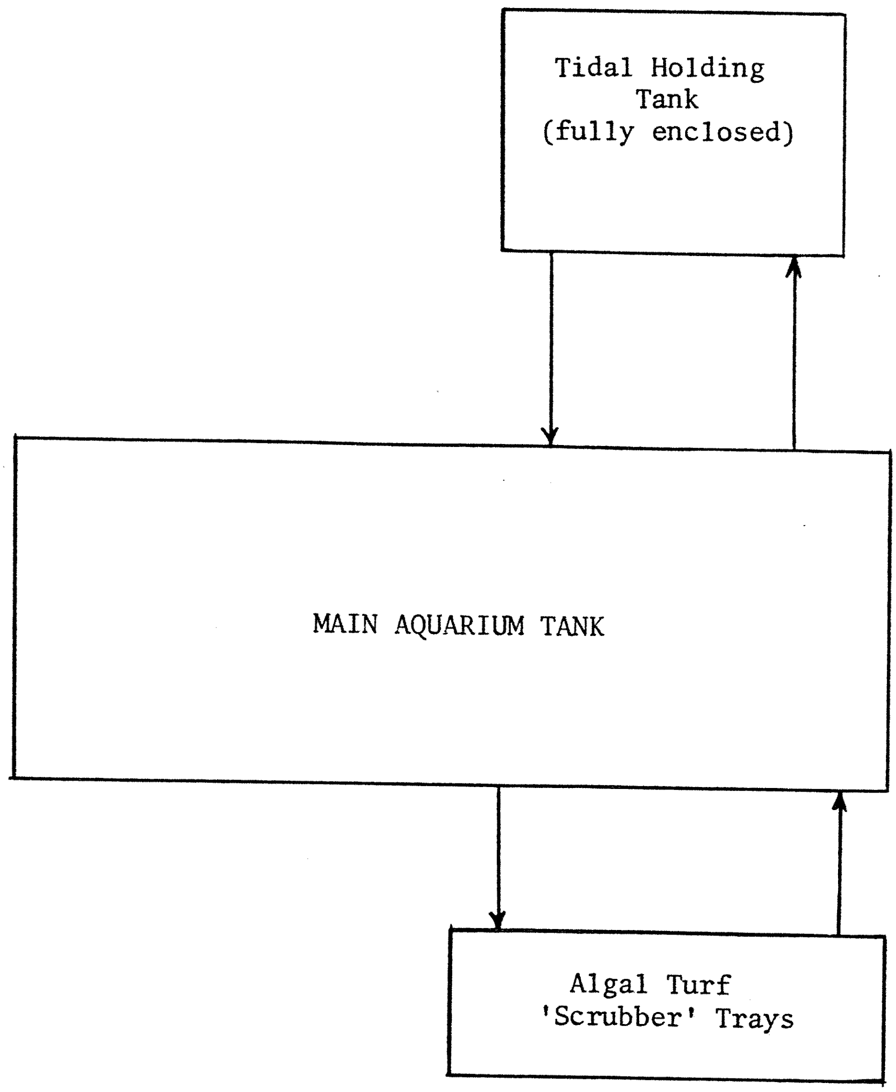


Figure 1

Schematic representation of the system studied

To make it possible, in the time available, to develop a workable model, a number of simplifying assumptions were necessary:

(i) Water in the aquarium is fully mixed. This should be a good approximation because of the continuous water circulation, and the turbulent mixing due to the wave making machine.

(ii) The only significant heat transfer mechanisms are: absorption of solar radiation; convection; and evaporation. The neglect of conductive heat transfers through the tank walls, and of re-radiation from the surface, appears justified in the light of solar collector and pond studies (Murthy, pers. comm.)

(iii) The tidal cycle has negligible effect on temperature variation. The tidal component will be mixed back into the tank twice each day and is therefore unlikely to differ significantly in temperature from the rest of the tank water.

(iv) The proportion of incident radiation absorbed is a constant. The true situation is, of course, much more complicated. The proportion of radiation absorbed at any time depends on many factors, including the angle of incidence of direct radiation; the relative proportions of direct and diffuse radiation; shading effects of nearby structures; state of the water surface; amount and properties of suspended matter, etc.

Consideration of such complexities is beyond the scope of this study, given the time constraints.

The implications of this simplification are difficult to judge.

3.2 Heat Transfer Mechanisms

3.2.1 Solar Radiation Absorption

A proportion of the incident radiation is reflected at the air-water interface. Different reflectivities apply for the direct and diffuse components of radiation. The relative proportions of these components depend very much on atmospheric conditions (i.e. scattering) as well as on reflections from nearby structures.

Reflectivity also depends on angle of incidence, which, for the direct component, varies from hour to hour (e.g. Rabl and Nielsen, 1975). Reflectivity at a clean, still water surface is 2% at normal incidence, increasing to only 3.3% at an angle of 50%. Reflectivity is strongly affected by the presence of material such as salt scale at the surface. It is also strongly affected by wave action at the surface.

Absorption and scattering of radiation occur in the water column. Experimental data for solar stills, as well as measurements in sea water, provide a guide to the absorptivity of the water. Some energy is reflected by the substrate and will then be absorbed in the water column as it passes back towards the surface. The remaining energy will be absorbed by the substrate, but forced convection due to water currents will quickly return this energy to the water column.

Because of the extreme complexity of the processes involved, and the limited time available, the model was simplified by

(i) not distinguishing between direct and diffuse radiation components;

(ii) assuming a <u>constant proportion of the incident global radiation energy is absorbed</u> by the mass of water.

This approach is consistent with earlier models of solar energy applications (e.g. Cooper, 1972; Rabl and Nielsen, 1975).

The proportion of radiation absorbed is a parameter of the model on which sensitivity analysis was carried out, and which can later be varied to give the best fit to calibration data, when they become available.

3.2.2 Evaporation and Convection

Heat transfer takes place between the water and the atmosphere, by evaporation and convection. These processes are modelled using a formulation developed and applied by Murthy and co-workers (e.g. Murthy, S.S. et al, 1974, 1976a, 1976b).

When heat is transferred between unsaturated air and a wetted surface, the driving force for the transfer is the "enthalpy potential". This is the difference between the enthalpy of unsaturated air and the enthalpy of saturated air at the temperature of the wetted surface.

Total heat transfer, dQ_t, is the sum of the sensible heat transfer, dQ_s, and the latent heat transfer, dQ_l. Under some simplifying assumptions which are well satisfied at normal temperatures, the heat transfer per unit area from surface to air can be written as:

$$\frac{dQ_t}{dA} = \frac{h}{1.025} (H_s - H_o),$$

where: h = coefficient of convective heat transfer;

H_s = enthalpy of saturated air at the surface temperature, t_s;

H_o = enthalpy of unsaturated air, at the air temperature.

The coefficient of convective heat transfer, h, is a function of the temperature difference between the surface and the air; wind velocity; Reynolds number; Prandtl number; thermal conductivity; density; viscosity and specific heat of the air. It is also dependent on whether flow over the surface is turbulent or laminar.

Standard correlations for h are published for a variety of situations, including heat transfer to a flat horizontal plate (Wong, 1977, p.52; Kreith, 1973, p. 398). These correlations were used to compute h, with a correction factor for buoyancy effects (Sparrow and Minkowycz, 1962) included in the case of laminar flows over the surface.

The following scheme was used, in which

V = wind velocity;

T_s = surface temperature;

T = air temperature;

Gr = Grashof number (proportional to $L^3(T_s-T)$);

Pr = Prandtl number;

k = thermal conductivity of the air;

L = characteristic dimension of the flat surface (length + breadth)/2;

Re = Reynolds number (proportional to LV).

```
IF(V=0.0)
  THEN IF(T_s>T)
        THEN IF(10^3<GrPr<10^9)
              THEN Free Laminar convection;
```

$$h = 0.54(GrPr)^{1/4}\frac{k}{L}$$

```
              ELSE IF(GrPr>10^9)
                    THEN Free turbulent convection
```

$$h = 0.14(GrPr)^{1/3}\frac{k}{L}$$

```
                    ELSE h = 0.0
                  ENDIF
        ELSE IF(GrPr>10^3)
              THEN h = 0.27(GrPr)^(1/4) k/L
              ELSE h = 0.0
             ENDIF
     ENDIF
ELSE IF(Re<5x10^5)
      THEN Laminar flow:
          IF(T_s>T)
            THEN h = h_forced (1 + Correction factor)
```

where $h_{forced} = 0.664\, Re^{1/2} Pr^{1/3} \frac{k}{L}$;

$$correction = 0.61\,\frac{Gr}{Re^{2.5}}$$

```
            ELSE h = h_forced (1 - Correction factor)
          ENDIF
      ELSE Re>5x10^5 : Turbulent flow;
```

$$h = h_{forced} = 0.037\, Re^{4/5} Pr^{1/3} \frac{k}{L}$$

```
     ENDIF
ENDIF
```

Published data are available for the enthalpy, H_s, for various values of T_s(ASHRAE, 1977, Chapter 6), with a reference base temperature of -17.8°C (0°F). A quadratic function $H_s(T_s)$ was fitted to these data over the range of temperatures of interest (15°C to 35°C). The SPSS package was used to develop this function.

The enthalpy of unsaturated air at temperature T is given by

$$H_o = \phi H_s(T) + C_p(T + 17.8)\ (1-\phi),$$

where ϕ = relative humidity of the air;

C_p = specific heat of dry air;

$H_s(T)$ is the saturation enthalpy calculated using the earlier relation, but at temperature T.

3.2.3 Effect of Wind Blockage

The coefficient of convective heat transfer is strongly dependent on wind speed over the surface. Reference to the aquarium design (Figure 2) shows a low structure along the north-eastern side of the main tank. Inspection of the tank shows that this structure causes a significant blockage of the wind, particularly from the north-east. The effect of this blockage is difficult to assess. It is accounted for in the model by multiplying the wind speed by a factor whose value depends on the wind direction. The factor is unity for wind directions other than north-easterly, and less than unity otherwise.

The wind reduction factor is another parameter on which sensitivity analysis is carried out, and which can later be used to calibrate the model, when data become available.

3.3 Algal Turf Trays

Water in the main tank is circulated through the algal turf 'scrubber' trays once every 24 hours. Retention time in the trays is approximately 2 1/2 minutes.

The same heat transfer processes are assumed to operate at the surfaces of the algal trays as have been discussed for the main tank. Preliminary simulations indicate that a temperature rise of less than $0.6^{o}C$ can be expected during passage through the trays.

It is therefore reasonable to assume that the algal trays are at the same temperature as the main tank, and merely act as additional interface area between the main tank and the atmosphere.

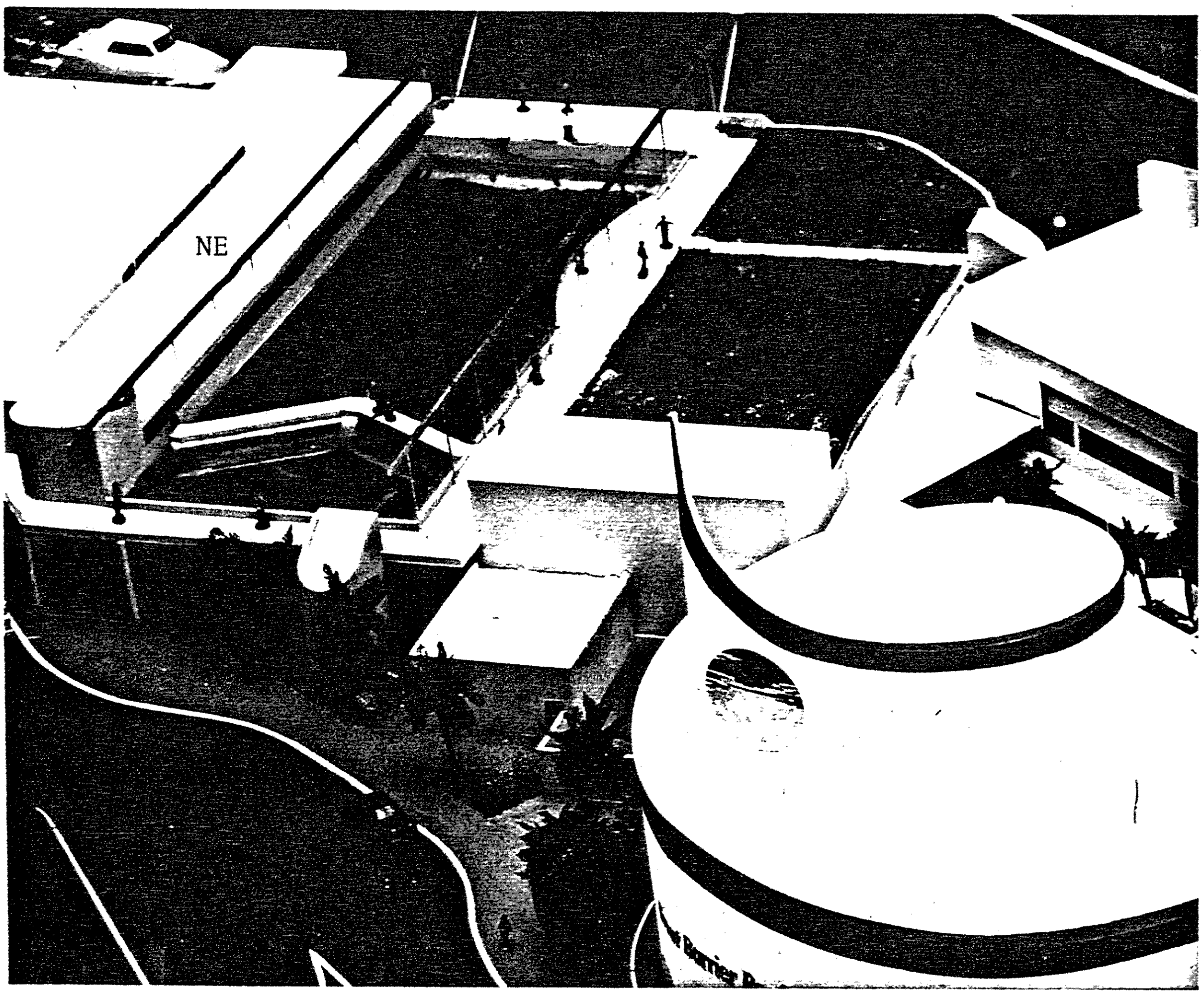


Figure 2

Aquarium main tank, with structure along NE side

3.5 Numerical Integration

The model is essentially a single first-order non-linear differential equation for the water temperature as a function of time. Given the various uncertainties surrounding some of the assumptions and parameter values employed, a sophisticated numerical integration is not warranted. Single step Euler integration is therefore used, with a time step of one hour.

4. DATA ANALYSIS

4.1 Meteorological Data

Extensive meteorological records were available on the University computer. Data for the Garbutt weather station included three-hourly air temperature, dew point temperature, and wind speed (ten-minute averages).

Standard transformations (ASHRAE, 1977) were used to obtain relative humidities from the dew point and dry-bulb temperatures.

Also available were monthly figures giving the percentage occurrence of wind speed versus direction, based on thirty-nine years of records, for 9 am and 3 pm (Table 1). These were used as a basis for varying the wind blockage factor discussed in Section 3.2.3.

The three-hourly data were converted to hourly values by linear interpolation, to give a record to match the hourly radiation data which were available (see below).

4.2 Solar Radiation Data

Global solar radiation density on a horizontal surface provides the chief energy input to the aquarium. Data for Townsville were available on the computer for only one year, 1975. The remaining data, in hard copy form, contained many gaps. Data for one additional year, 1976, were punched into the computer.

Simulation runs were made using the 1975-76 data. Considerable differences in temperatures for the two years were observed, mainly due to differences in meteorological conditions (especially wind speed). It was therefore recognized that longer runs were necessary to obtain a more reliable indication of long term behaviour.

	Most Likely Direction	
	Morning	Afternoon
Jan	SE	NE
Feb	SE	NE
Mar	SE	NE
Apr	SE	NE
May	SE	NE
Jun	SE	NE
Jul	S	NE
Aug	SE	NE
Sep	E	NE
Oct	E	NE
Nov	NE	NE
Dec	ENE	NE

<u>Table 1</u>

Wind Direction Data

This was achieved by using synthetic radiation data generated by a model based on the 1975-76 data, as follows.

The 1975-76 data were used to develop a simple linear regression between total daily radiation, and the difference between daily maximum air temperature, and the air temperature at 5 am (i.e. the daily temperature rise).

A separate regression model was developed for each month (Table 2). The relationships were not very strong, but examination of the residuals indicated a reasonably symmetric distribution about the regression line in each case.

Therefore, for each day in any particular month, a synthetic value for total daily radiation is generated by Monte Carlo sampling from a normal distribution about the regression line, given the rise in air temperature for that day.

The total daily radiation is then used to derive <u>hourly</u> values by using a tabular representation of Liu-Jordan charts (Duffie and Beckman, 1974, p. 46; Whillier, 1965). As an example of this transformation, consider the <u>real</u> data for January 1, 1975. The total daily radiation was 16.91 MJ/m^2, from which the Whillier table gives hourly radiation between 1 pm and 2 pm of 2.03 MJ/m^2. This compares quite well with the <u>real</u> hourly radiation from 1 pm to 2 pm of 1.92 MJ/m^2.

4.3 <u>Fixed Parameters</u>

System parameter values used in the model are presented in Table 3.

Uncertainty surrounds the values of the wind blockage factor; the energy incident on the algal trays from the lamps used to irradiate the trays at night; the fraction of incident radiation absorbed by the water. Table 3 shows the sets of values used for these parameters. Simulation runs were carried out for all combinations of these values.

Each algal tray area of 2.1 m^2 is illuminated by two lamps, each rated at 1000 watts. The amount of radiation energy incident on the trays depends on the lamp efficiencies and the effectiveness of the geometrical arrangement. It was suggested (G. Just, personal communication) that an overall figure of 40% may be appropriate. The value of 1800 kJ/m^2 hr corresponds to 50%.

Month	1	2	3	4	5	6	7	8	9	10	11	12
r	0.73	0.74	0.59	0.56	0.66	0.65	0.37	0.63	0.36	0.55	0.57	0.67

Table 2

Correlation between total daily radiation and daily temperature rise ($T_{max} - T_{5\ am}$)

Tank	Surface area of water (m^2)	580
	Mass of water (kg)	2.6×10^6
	Wind blockage factor	0.6, 0.8, 1.0
Algal Trays	Surface area (m^2)	100
	Irradiation (kJ/m^2hr)	500, 1000, 1800
Physical Properties	Specific heat of water (kJ/kg^oC)	4.19
	Prandtl number	0.7
	Fraction of radiation absorbed	0.5, 0.6, 0.7

Table 3

System parameters

The absorption of incident radiation depends on a number of complex processes, as discussed in Section 3.2.1. Some data are available for clean sea water (e.g. Cooper, 1972; Rabl and Nielsen, 1975). Typical values are presented in Table 4.

Specular reflection at the surface of clean, still water ranges from 2% at an incident angle of 0^{o}, to 3.3% at 50^{o}, and to 34.7% at 80^{o} (Rabl and Nielsen, 1975). That is, the great proportion of incident direct radiation suffers only a few percent reflection at a clean, still surface. Diffuse radiation experiences greater reflection (approximately 6% (Rabl and Nielsen, 1975)).

The presence of waves and particulate matter on the water surface will increase the reflectivity (Cooper, 1972).

These data suggest that significantly less than 80% of the incident radiation will be absorbed in the aquarium water column. Therefore simulation runs were made with proportions 0.5, 0.6, and 0.7 of the radiation absorbed. For simplicity, and to reduce the number of parameters to be fitted to calibration data at a later time, the same proportion was assumed for the algal trays.

5. SIMULATION OUTPUT ANALYSIS

5.1 Model Tests

The coded model was extensively tested for a variety of combinations of initial water temperature, fixed air temperature, fixed radiation level, fixed wind speed and fixed relative humidity. This ensured that the model response, and steady state temperature reached, were physically realistic.

5.2 Simulation Runs

Aquarium temperature variation was simulated using the real solar radiation data for 1975 and 1976. Standard ten-year runs were then made using synthetic radiation data, and meteorological data for 1960-69.

Experimental runs were finally made in which the effects of shading the water surface were investigated.

	Depth (m)	Percentage Absorbed
Cooper	1	52%
Rabl & Neilsen	1	73%
Cooper	10	64%
Rabl & Neilsen	10	83%

Table 4

Absorptivity of sea water

5.3 Frequency Analyses

The hourly temperature records produced by the model were analysed to produce a set of summary statistics. These include:

- Relative frequency histograms of daily maxima, minima and ranges
- Daily probabilities of exceedence of limiting values
- Lengths of runs of consecutive days on which
  - (a) maximum temperature exceeds the tolerable limit;
  - (b) minimum temperature is less than the tolerable limit;
  - (c) daily range exceeds the tolerable limit.

5.4 Results of Standard Runs

Figures 3, 4 and 5 present the relative frequency histograms resulting from the 10 years' simulations for three combinations of values of the uncertain parameters discussed in Section 4.3. Figure 3 results from the combination of medium values of the parameters: 60% of incident radiation absorbed; a wind blockage factor of 0.8; and algal tray irradiation of 1000 kJ/m^2. This will be referred to as the medium combination.

Figure 4 represents the combination of values which are most favourable, in the sense of minimising the temperatures reached: 50% of incident radiation absorbed; a wind blockage factor of 1.0; and algal tray irradiation of 500 kJ/m^2 hr.

Figure 5 represents the opposite extreme, being the combination which leads to the highest temperatures: 70% of incident radiation absorbed; a wind blockage factor of 0.6; and algal tray irradiation of 1800 kJ/m^2 hr. This will be referred to as the extreme combination.

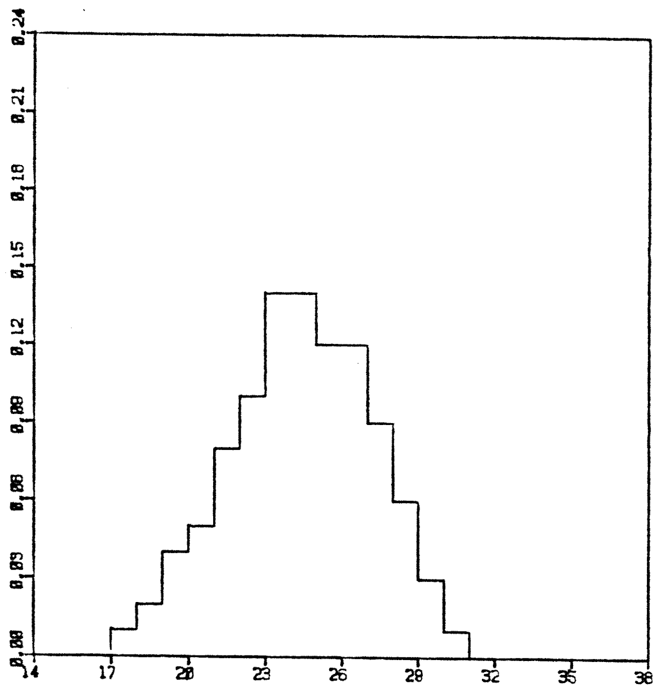
Tables 5 and 6 present probabilities of exceedence. In Table 5, P_T is the proportion of daily maxima which exceed T. In Table 6, Q_T is the proportion of daily minima which are less than T, and P_R is the proportion of daily temperature ranges which exceed R. These proportions are calculated from the 10 years simulations and are given for all 27 combinations of values of the three parameters.

FRACTION OF RADIATION ABSORBED = Ø.6

WIND REDUCTION FACTOR = Ø.8

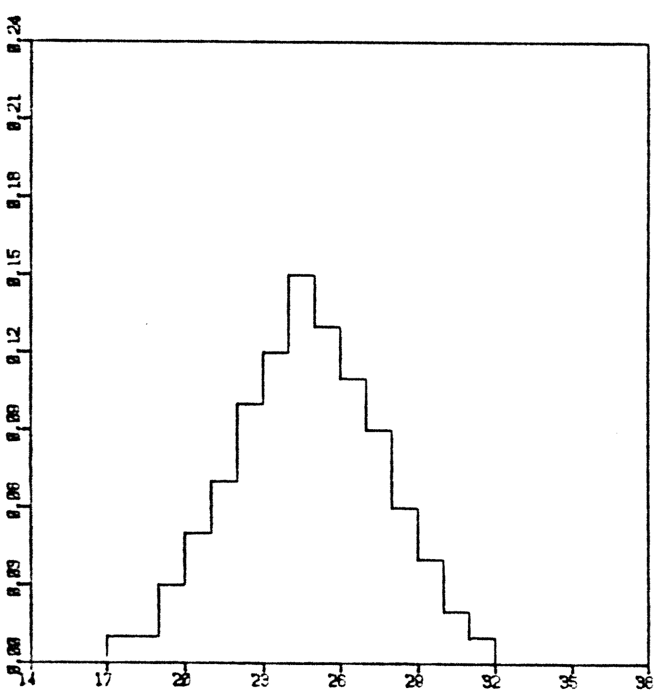
ALGAL TRAY IRRADIATION = 1ØØØ

MINIMA



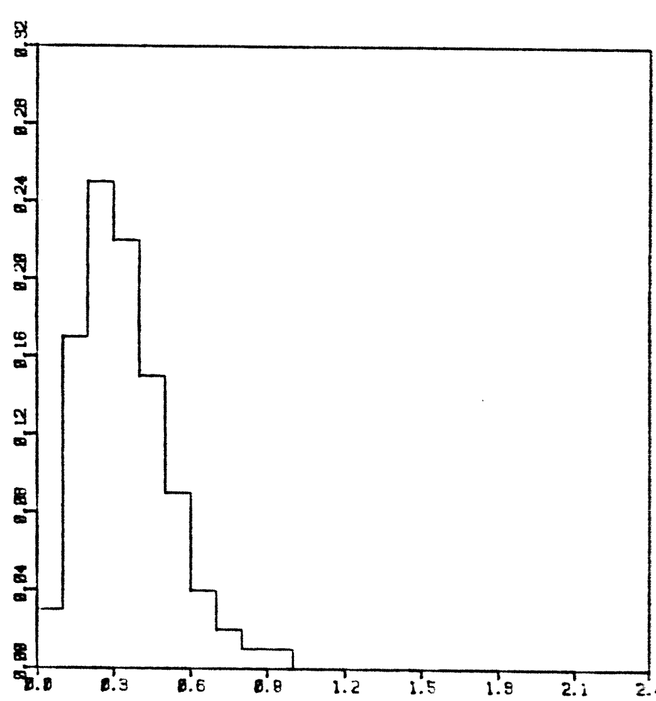
Temperature, °C

MAXIMA



Temperature, °C

RANGE



Temperature, °C

Figure 3

Parameter combination number 14

FRACTION OF RADIATION ABSORBED = 0.5

WIND REDUCTION FACTOR = 1.0

ALGAL TRAY IRRADIATION = 500

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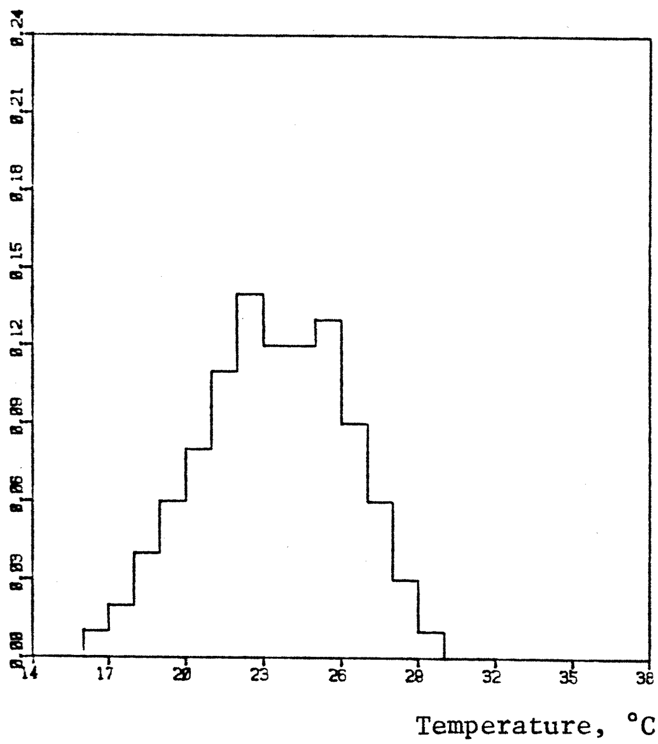
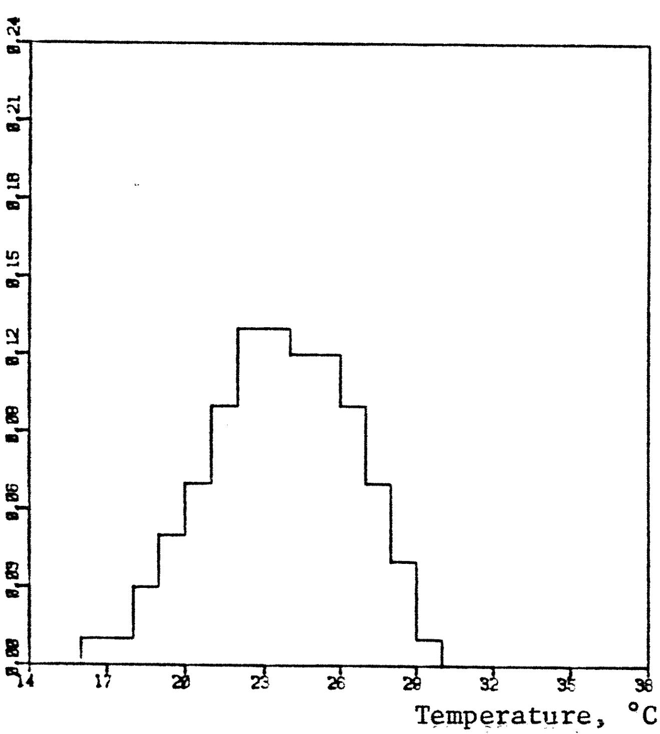


MAXIMA



RANGE

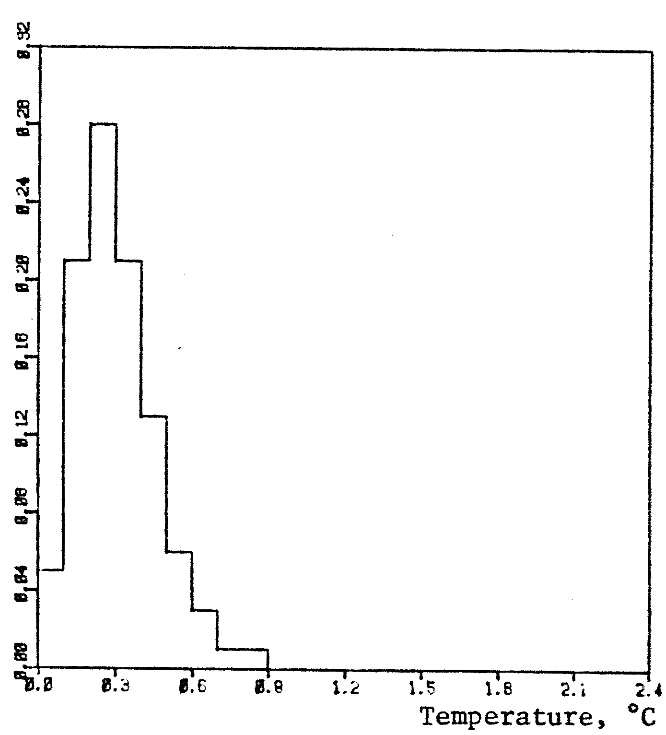


Figure 4

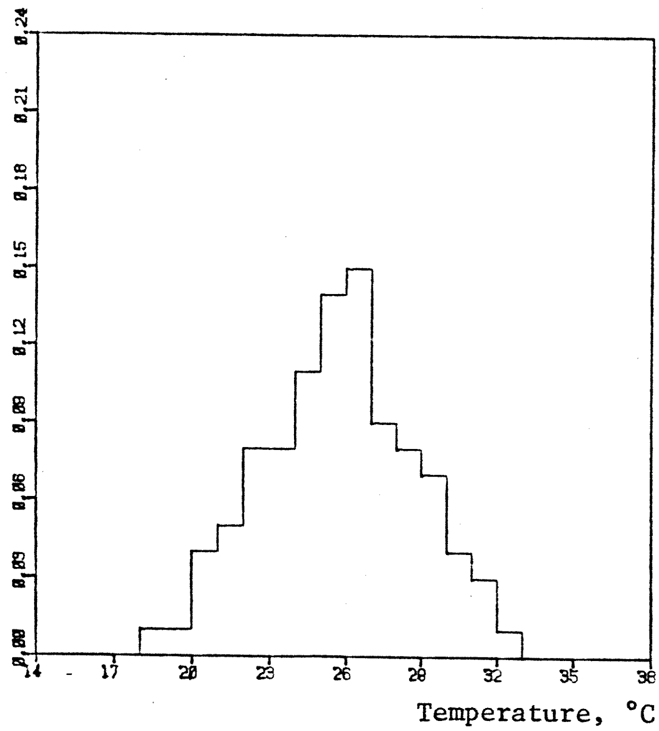
Parameter combination number 7

FRACTION OF RADIATION ABSORBED = 0.7

WIND REDUCTION FACTOR = 0.6

ALGAL TRAY IRRADIATION = 1800

MINIMA



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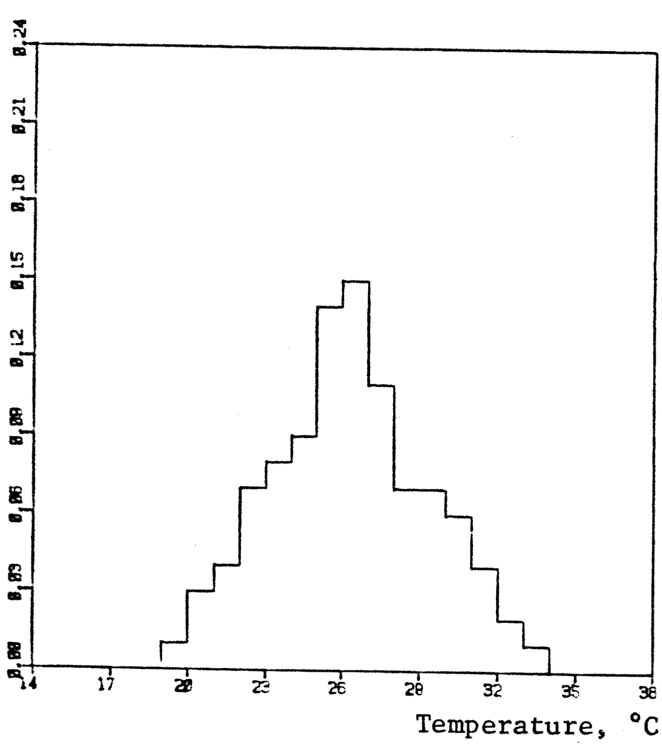

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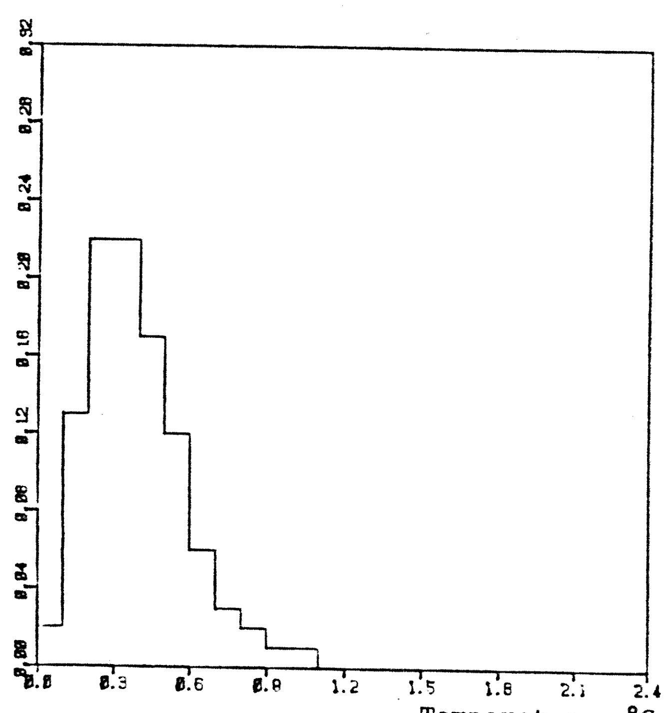

Figure 5

Parameter combination number 21

DAILY MAXIMA

	Fraction of Radiation Absorbed	Wind Reduction Factor	Algal Tray Radiation	P_{28}	P_{29}	P_{30}	P_{31}	P_{32}	P_{33}
1	0.5	0.6	500	0.12	0.05	0.02	0.0	0.0	0.0
2	0.5	0.6	1000	0.13	0.06	0.02	0.0	0.0	0.0
3	0.5	0.6	1800	0.13	0.06	0.02	0.0	0.0	0.0
4	0.5	0.8	500	0.07	0.02	0.0	0.0	0.0	0.0
5	0.5	0.8	1000	0.08	0.03	0.0	0.0	0.0	0.0
6	0.5	0.8	1800	0.10	0.04	0.01	0.0	0.0	0.0
7	0.5	1.0	500	0.05	0.01	0.0	0.0	0.0	0.0
8	0.5	1.0	1000	0.05	0.01	0.0	0.0	0.0	0.0
9	0.5	1.0	1800	0.07	0.02	0.0	0.0	0.0	0.0
10	0.6	0.6	500	0.19	0.11	0.05	0.02	0.0	0.0
11	0.6	0.6	1000	0.19	0.11	0.05	0.02	0.0	0.0
12	0.6	0.6	1800	0.22	0.14	0.07	0.03	0.01	0.0
13	0.6	0.8	500	0.12	0.06	0.02	0.0	0.0	0.0
14	0.6	0.8	1000	0.13	0.07	0.03	0.01	0.0	0.0
15	0.6	0.8	1800	0.14	0.08	0.03	0.01	0.0	0.0
16	0.6	1.0	500	0.10	0.04	0.01	0.0	0.0	0.0
17	0.6	1.0	1000	0.10	0.04	0.01	0.0	0.0	0.0
18	0.6	1.0	1800	0.10	0.04	0.01	0.0	0.0	0.0
19	0.7	0.6	500	0.24	0.17	0.09	0.04	0.01	0.0
20	0.7	0.6	1000	0.26	0.19	0.11	0.06	0.03	0.01
21	0.7	0.6	1800	0.27	0.20	0.13	0.07	0.03	0.01
22	0.7	0.8	500	0.17	0.10	0.05	0.02	0.0	0.0
23	0.7	0.8	1000	0.19	0.11	0.06	0.03	0.01	0.0
24	0.7	0.8	1800	0.20	0.12	0.07	0.03	0.01	0.0
25	0.7	1.0	500	0.13	0.07	0.03	0.01	0.0	0.0
26	0.7	1.0	1000	0.15	0.09	0.04	0.01	0.0	0.0
27	0.7	1.0	1800	0.15	0.09	0.04	0.01	0.0	0.0

Table 5

10 Years' Simulation

	Fraction of Radiation Absorbed	Wind Reduction Factor	Algal Tray Radiation	DAILY MINIMA Q_{16}	Q_{17}	Q_{18}	Q_{19}	DAILY RANGE $P_{1.0}$	$P_{1.5}$
1	0.5	0.6	500	0.0	0.0	0.01	0.04	0.0	0.0
2	0.5	0.6	1000	0.0	0.0	0.01	0.03	0.0	0.0
3	0.5	0.6	1800	0.0	0.0	0.01	0.03	0.0	0.0
4	0.5	0.8	500	0.0	0.01	0.02	0.05	0.0	0.0
5	0.5	0.8	1000	0.0	0.01	0.02	0.05	0.0	0.0
6	0.5	0.8	1800	0.0	0.0	0.01	0.04	0.0	0.0
7	0.5	1.0	500	0.0	0.01	0.03	0.07	0.0	0.0
8	0.5	1.0	1000	0.0	0.01	0.02	0.06	0.0	0.0
9	0.5	1.0	1800	0.0	0.01	0.02	0.05	0.0	0.0
10	0.6	0.6	500	0.0	0.0	0.01	0.02	0.0	0.0
11	0.6	0.6	1000	0.0	0.0	0.01	0.02	0.0	0.0
12	0.6	0.6	1800	0.0	0.0	0.0	0.01	0.0	0.0
13	0.6	0.8	500	0.0	0.0	0.01	0.03	0.0	0.0
14	0.6	0.8	1000	0.0	0.0	0.01	0.03	0.0	0.0
15	0.6	0.8	1800	0.0	0.0	0.01	0.02	0.0	0.0
16	0.6	1.0	500	0.0	0.0	0.01	0.04	0.0	0.0
17	0.6	1.0	1000	0.0	0.0	0.01	0.03	0.0	0.0
18	0.6	1.0	1800	0.0	0.0	0.01	0.03	0.0	0.0
19	0.7	0.6	500	0.0	0.0	0.0	0.01	0.01	0.0
20	0.7	0.6	1000	0.0	0.0	0.0	0.01	0.01	0.0
21	0.7	0.6	1800	0.0	0.0	0.0	0.01	0.01	0.0
22	0.7	0.8	500	0.0	0.0	0.01	0.02	0.01	0.0
23	0.7	0.8	1000	0.0	0.0	0.0	0.01	0.01	0.0
24	0.7	0.8	1800	0.0	0.0	0.0	0.01	0.01	0.0
25	0.7	1.0	500	0.0	0.0	0.01	0.02	0.01	0.0
26	0.7	1.0	1000	0.0	0.0	0.01	0.02	0.01	0.0
27	0.7	1.0	1800	0.0	0.0	0.01	0.02	0.01	0.0

Table 6

10 Years' Simulations

Table 7 presents the longest runs of consecutive days on which

(a) the maximum temperature exceeds $31^{o}C$;
(b) the minimum temperature is less than $19^{o}C$.

It also presents the highest and lowest temperatures reached during those runs.

Table 8 presents the results of the two-years simulations (1975-1976), for one combination of parameters.

5.5 Discussion of Results

5.5.1 Daily Temperature Range

The daily variation is likely to be within the tolerable limit of $2^{o}C$. A range of $1^{o}C$ is exceeded on only a very small proportion of days (< 0.5, therefore shown as 0.0 in Table 6) for all parameter combinations.

5.5.2 Daily Maximum Temperature

The proportion of days on which the maximum temperature exceeds $31^{o}C$ is less than 10%, for all combinations of model parameters. The highest proportion, 7% occurs for combination 21, of high radiation absorption (70%) and a strong wind-blocking effect (40% reduction). In fact, under those conditions, $32^{o}C$ is exceeded 3% of the time, and $33^{o}C$ is exceeded 1% of the time.

Combination 21 represents the extreme case. Under the medium combination, number 14, the temperature of $31^{o}C$ is exceeded on about 1% of all days.

Under all combinations except the least favourable (19,20 and 21) the probability of exceeding $30^{o}C$ is at most only a few percent. However there is a very significant likelihood of exceeding $28^{o}C$ under all combinations.

5.5.3 Daily Minimum Temperature

For all combinations of parameters, the proportion of days on which the minimum temperature is less than $19^{o}C$ is no more than about 7%. In most cases it is less than 4%.

	Fraction Radiation Absorbed	Wind Reduction Factor	Algal Tray Radiation	Longest runs of consecutive days with:	
				$T_{max} > 31^oC$	$T_{min} < 19^oC$
1	0.5	0.6	500	6 (31.5)*	22 (15.9)*
2	0.5	0.6	1000	7 (31.6)	21 (16.0)
3	0.5	0.6	1800	8 (31.7)	19 (16.2)
4	0.5	0.8	500	0	23 (15.6)
5	0.5	0.8	1000	1 (31.01)	22 (15.7)
6	0.5	0.8	1800	3 (31.2)	20 (15.9)
7	0.5	1.0	500	0	45 (15.2)
8	0.5	1.0	1000	0	24 (16.1)
9	0.5	1.0	1800	0	22 (16.4)
10	0.6	0.6	500	36 (32.9)	15 (16.5)
11	0.6	0.6	1000	36 (33.1)	14 (16.7)
12	0.6	0.6	1800	36 (33.3)	13 (16.9)
13	0.6	0.8	500	7 (31.7)	17 (16.2)
14	0.6	0.8	1000	8 (31.8)	16 (16.3)
15	0.6	0.8	1800	9 (31.8)	14 (16.5)
16	0.6	1.0	500	3 (31.4)	18 (15.8)
17	0.6	1.0	1000	3 (31.5)	17 (16.0)
18	0.6	1.0	1800	4 (31.7)	16 (16.2)
19	0.7	0.6	500	41 (34.1)	12 (17.1)
20	0.7	0.6	1000	46 (33.1)	10 (17.3)
21	0.7	0.6	1800	53 (33.3)	7 (17.5)
22	0.7	0.8	500	22 (32.8)	13 (16.7)
23	0.7	0.8	1000	24 (32.3)	12 (16.9)
24	0.7	0.8	1800	36 (33.4)	10 (17.1)
25	0.7	1.0	500	9 (32.0)	13 (16.4)
26	0.7	1.0	1000	11 (31.7)	13 (16.5)
27	0.7	1.0	1800	13 (32.0)	12 (16.8)

*Extremes shown in parenthesis

Table 7

10 Years' Simulations

PROBABILITIES OF EXCEEDENCE							
P_{28}	P_{29}	P_{30}	P_{31}	P_{32}	Q_{17}	Q_{18}	Q_{19}
0.37	0.26	0.14	0.07	0.02	0.0	0.0	0.0

RUNS OF CONSECUTIVE DAYS WITH:

(a) $T_{max} > 31^{o}C$ = 30 (highest = $32.6^{o}C$)

(b) $T_{min} < 19^{o}C$ = 0

(c) Range $> 1^{o}C$ = 2

Table 8

2 Years' Simulation, 1975-76
Fraction of radiation absorbed = 0.6
Wind-reduction factor = 1.0
Algal tray radiation = 1800

Parameter Combination Number	Shading Reduction	Daily Maxima						Longest run of days with $T_{max} > 31^oC$
		P_{28}	P_{29}	P_{30}	P_{31}	P_{32}	P_{33}	
14	None	0.13	0.07	0.03	0.01	0.0	0.0	8
14	50%	0.07	0.02	0.0	0.0	0.0	0.0	0
21	None	0.27	0.20	0.13	0.07	0.03	0.01	53
21	50%	0.17	0.09	0.04	0.01	0.0	0.0	11

<u>Table 9</u>

Shading experiments

	Jan	Feb	Mar	Oct	Nov	Dec
1960	3.6	2.4	2.8	3.8	3.5	4.0
1961	3.6	3.4	2.8	3.8	3.8	3.6
1962	3.0	2.2	2.8	3.8	3.6	3.6
1963	2.5	2.6	2.6	3.6	4.0	3.8
1964	2.5	1.8	2.0	3.0	2.9	2.9
1965	3.1	2.8	2.1	3.8	3.7	3.3
1966	2.8	1.6	2.3	3.6	3.9	3.8
1967	2.9	3.5	3.0	2.9	3.5	2.2
1968	2.2	2.1	1.5	3.3	2.7	2.8
1969	2.6	2.6	3.5	4.1	3.6	3.4

<u>Table 10</u>

Monthly average wind speeds (m/sec)

5.5.4 Runs of Consecutive Highs

Table 7 shows that for some combinations of parameters there may occur long periods of sustained high temperatures. Such periods are likely to prove more destructive than occasional very extreme temperatures.

For the medium case (combination 14), the longest 'run' is 8 days. However for the extreme case (combination 21), high temperature periods of between one and two months could be expected.

5.5.5 The 1975-76 Simulation

Table 8 shows an extended period of 30 days during which the daily maxima were all in excess of 31°C. The results of this simulation were examined more closely and it was found that this period of high water temperature occurred during a period of great calm - recorded wind speeds were zero for days on end.

This serves to emphasize the sensitivity of aquarium temperature to variations in wind speed (the major cooling mechanism is forced convection). This is also evident from Tables 5 and 6, showing sensitivity of the results to variation in the wind-reduction factor.

6. TEMPERATURE CONTROL

The model was used to investigate the effectiveness of temperature control by shading the water surface (e.g. using shade-cloth).

In these experiments, 50% shading was applied between the hours of 10 am and 3 pm, during the hotter months (October to March inclusive). The medium and extreme parameter combinations were used. The results are presented in Table 9.

Shading in this manner has a significant effect on the upper tails of the distributions and on the durations of periods of high temperatures (above 31°C). In fact, for the medium case, the water temperature did not exceed 31°C on any days.

In the extreme case, 31°C was exceeded on a total of 47 days in the ten years simulated. Runs of consecutive days on which the temperature exceeded 31°C were as follows:

9 4 2 11 3 1 3 2 3 5 1 3.

There were 4 days on which 32°C was exceeded.

The days on which these extremes occurred were identified, and the meteorological records for those days were inspected. It was found that the temperature extremes coincided with warm, very calm conditions, from October 1967 to March 1968. Average wind speeds (m/sec) for these months, for the years 1960 to 1969 are presented in Table 10.

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APPENDIX

SOFTWARE

The software system developed for this study is represented in figures A1, A2, A3, A4 and A5.

Data files and FORTRAN programs are identified as follows:

TOWNSV.WTC	:	Meteorological data for Townsville (3-hourly 1960-69) (Courtesy of Mr. M. Crees)
RELHUM.FOR	:	Subroutine to calculate relative humidity, given dry-bulb and dew point temperatures (Courtesy of Mr. M. Crees)
MET.FOR	:	Reads TOWNSV.WTC, calculates relative humidities, and outputs air temperature, wind speed, and relative humidity to MET.DAT
MET.DAT	:	Three-hourly air temperature, wind speed and relative humidity
METINT.FOR	:	Converts three-hourly met. data to one-hourly data by linear interpolation
FORØ4.DAT	:	Hourly wind speed, with year, month and day
FORØ6.DAT	:	Hourly air temperature, with year, month and day
FORØ7.DAT	:	Hourly relative humidity, with year, month and day
TOWNSV.GLC	:	Global radiation data for Townsville (hourly) (1975)
RAD.FOR	:	Reads TOWNSV.GLC and writes to RAD.DAT
RAD75.76	:	RAD.DAT renamed, and radiation data for 1976 added
FOR4Ø.DAT	:	Number of days in each month

LINMOD.FOR	:	Fits linear regression between total daily radiation and daily temperature rise
FOR55.DAT	:	Linear regression coefficients and error standard deviation, for each month
FOR6Ø.DAT	:	Daily total radiation; daily temperature rise
RESIDU.FOR	:	Computes residuals and outputs for checking
FOR56.DAT	:	Residuals from linear regression
FORØ1.DAT	:	Initial conditions; thermodynamic parameters
FORØ2.DAT	:	Tank parameters
TNKSIM.FOR	:	Simulation program
IMSL:GGNQF	:	Subroutine from IMSL package: generates standard normal variates
FORØ8.DAT	:	Hourly aquarium temperature; day, month, year
FOR2Ø.DAT	:	Tolerance limits for max, min and range
TNKOUT	:	Simulation output analysis program
FOR21.DAT - FOR31.DAT	:	Output files (defined in the program TNKOUT)
HIST1.FOR	:	Computes histograms
MINHST.*	:	Histogram of daily minima ('*' denotes number of run)
MAXHST.*	:	Histogram of daily maxima
RNGHST.*	:	Histogram of daily temperature ranges
HUMWIN.DAT	:	Meteorological data for Townsville (3-hourly, 1975-76) (Courtesy of M. Crees)

MET756.FOR	:	Reads HUMWIN.DAT; as for MET.FOR
TANK.FOR	:	Simulation program, using 1975-76 radiation data

ANALYSIS OF METEOROLOGICAL DATA (1960-69)

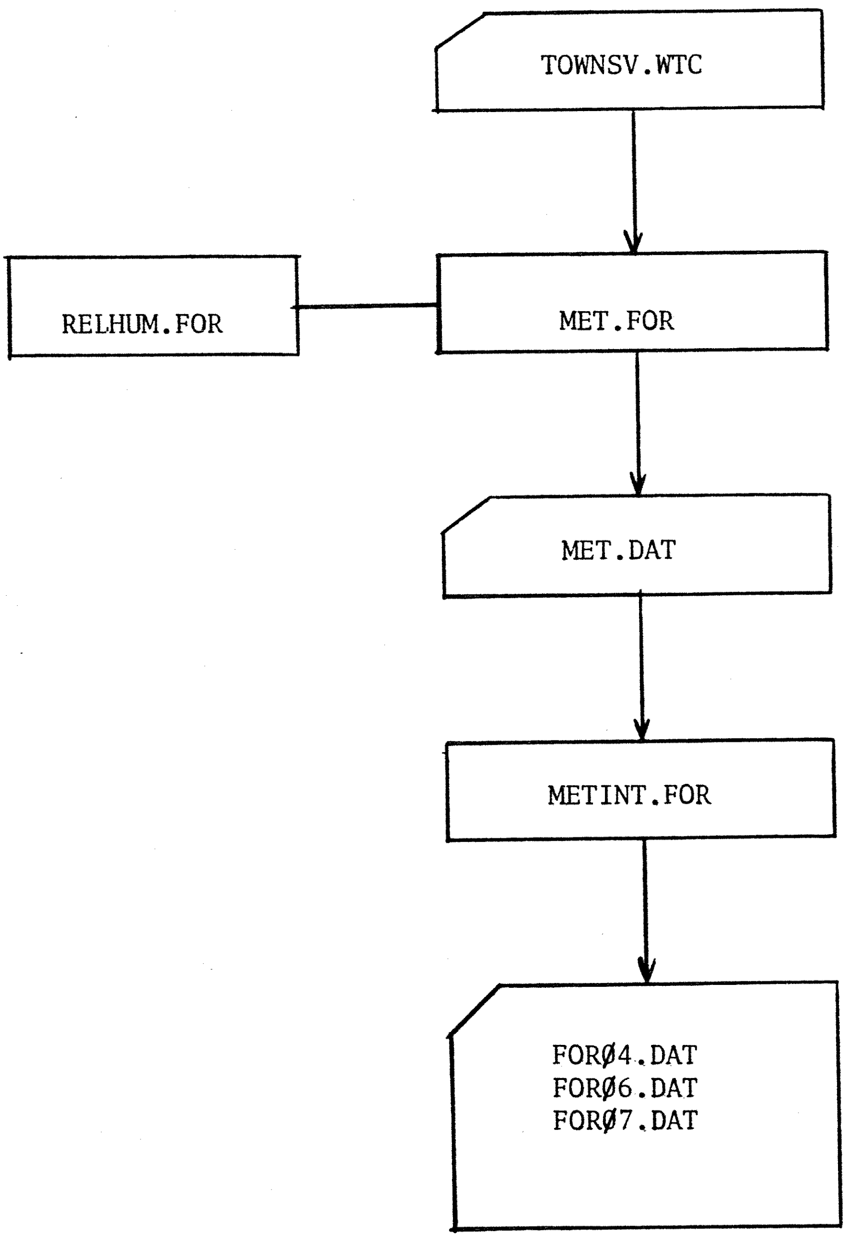

Figure A1

ANALYSIS OF RADIATION DATA

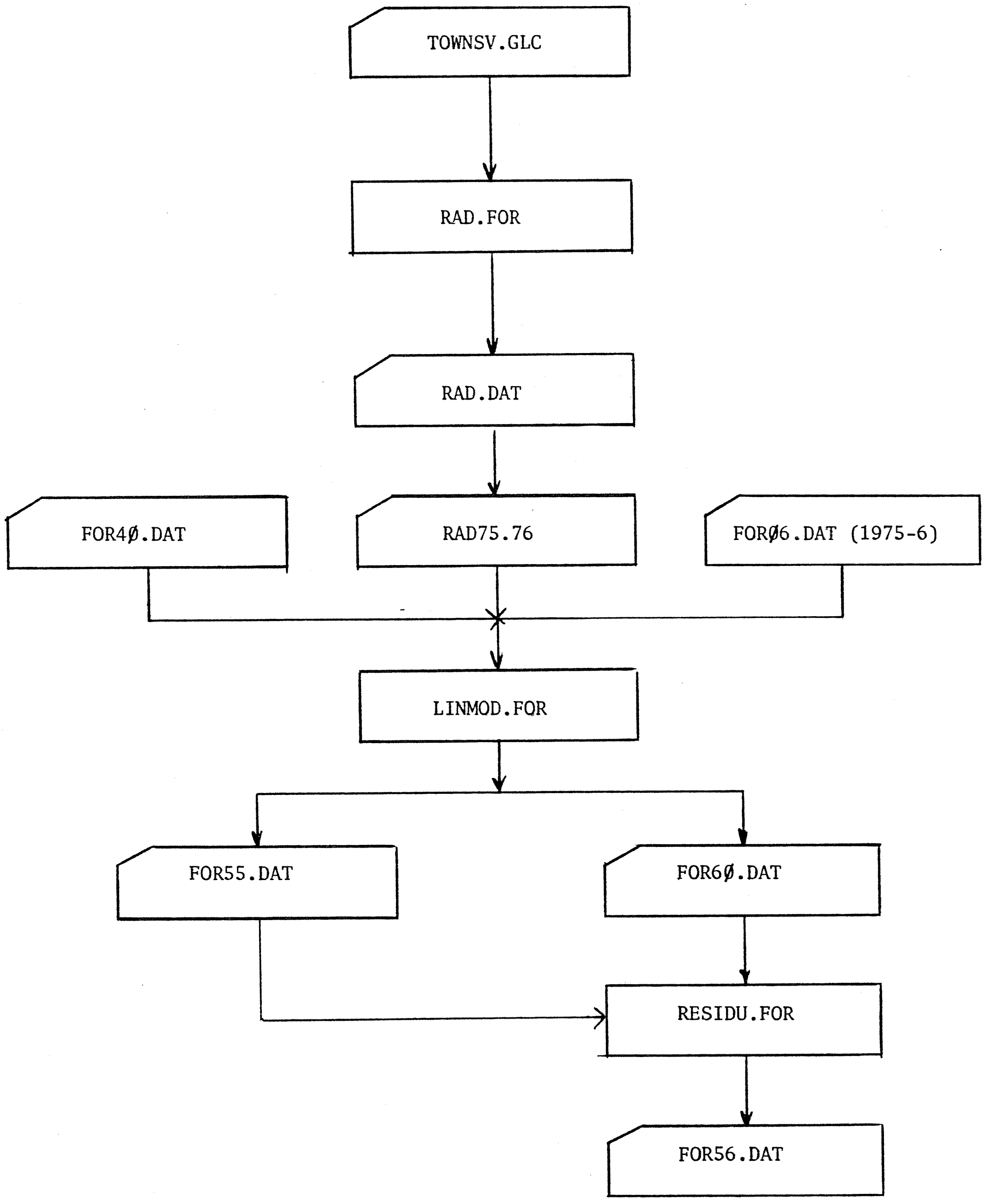

Figure A2

SIMULATION OF AQUARIUM TEMPERATURE
1960-69

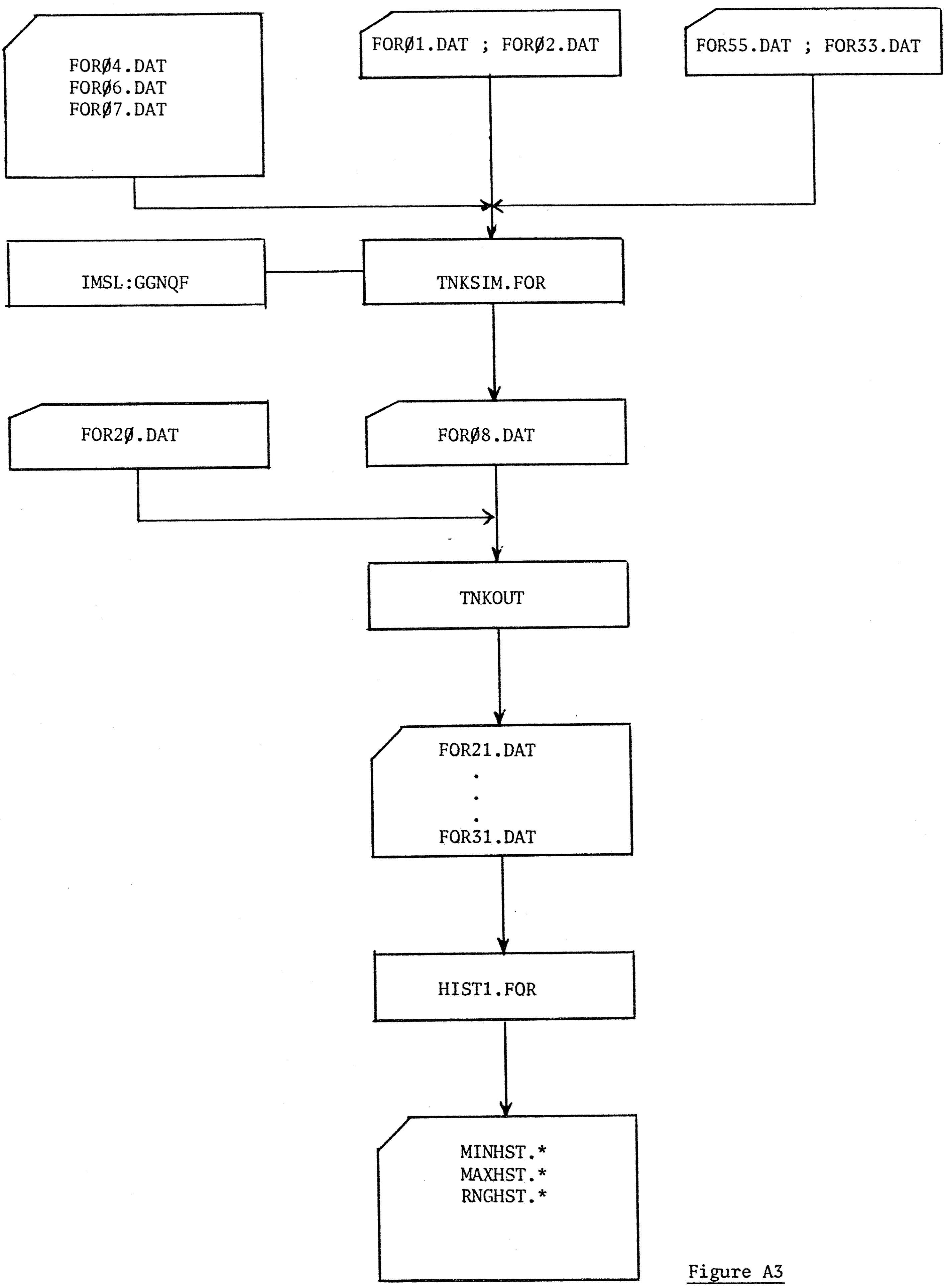

Figure A3

ANALYSIS OF METEOROLOGICAL DATA
1975-76

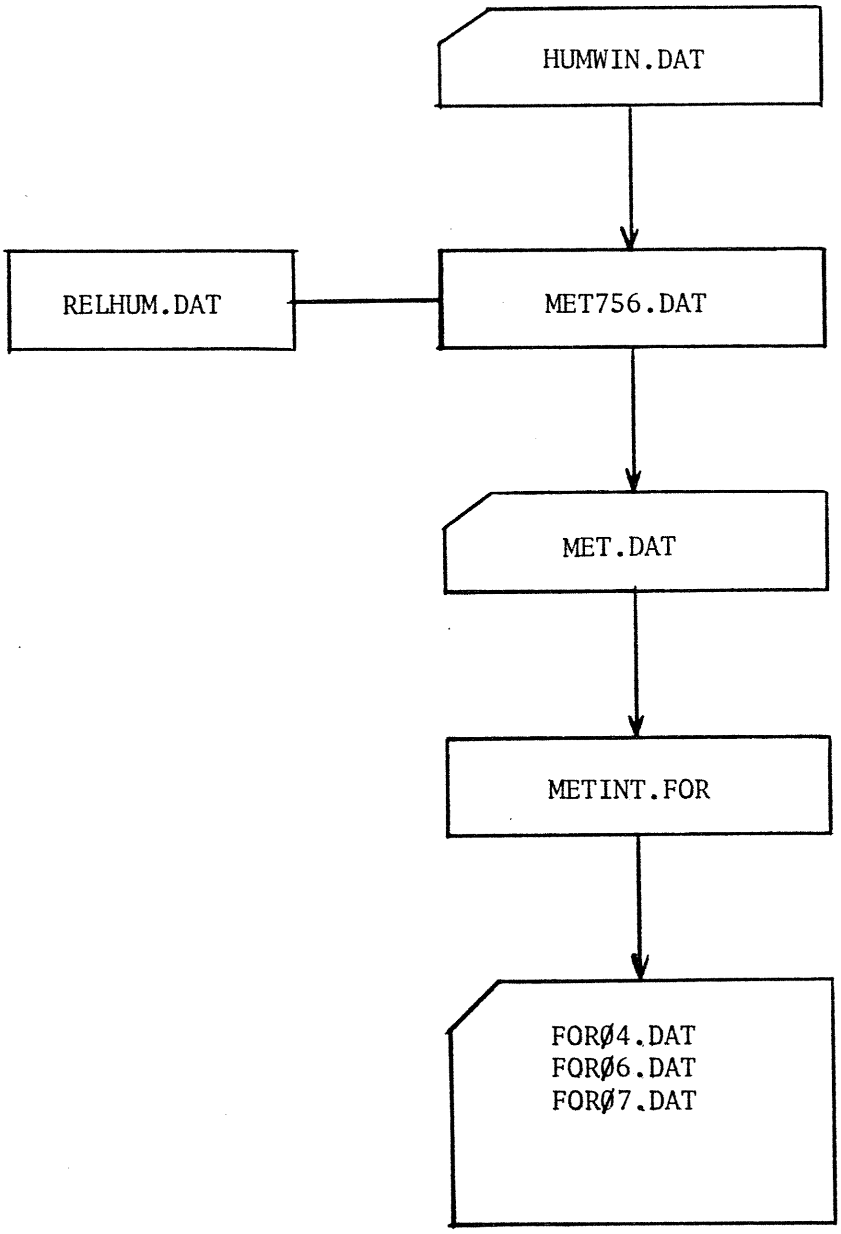

Figure A4

SIMULATION OF AQUARIUM TEMPERATURE
1975-76

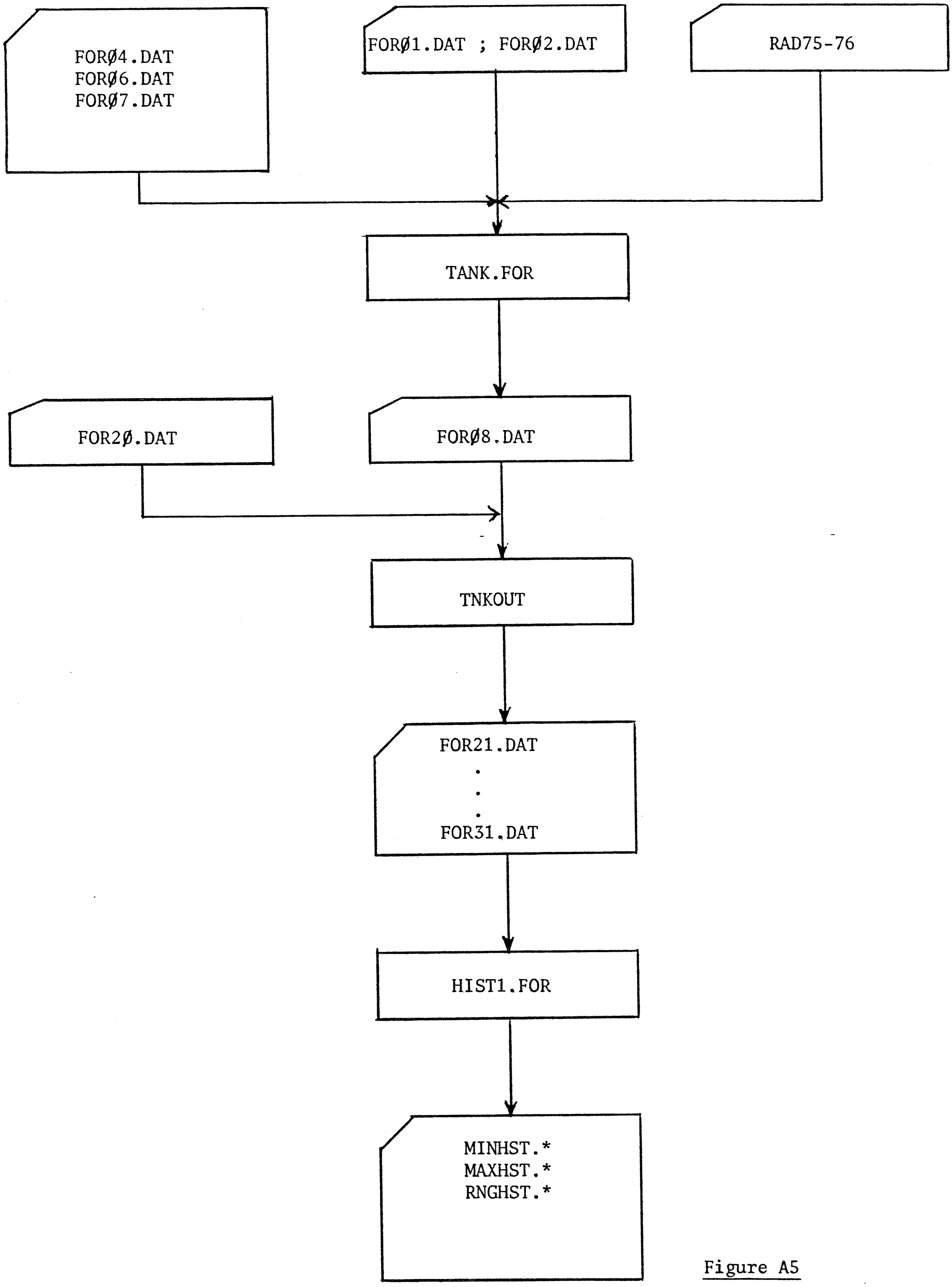

Figure A5