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RECORD

Record No. 1990/42

Corrections for Marine heat flow Measurements

by

T. Lee , R. Lewis

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Heat has been defined in the foregoing section as a motion of the molecules or atoms of a body; but though the evidence in favour of this view is at present overwhelming, I do not ask the reader to accept it as a certainty, if he feels sceptically disposed. In this case, I would only ask him to accept it as a symbol. Regarded as a mere physical image, a kind of paper-currency of the mind, convertible, in due time, into the gold of truth, the hypothesis will be found exceedingly useful.

John Tyndall, FRS, The Glaciers of the Alps, 1860, p241

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SUMMARY

Calculations for the modelling of thermal probes in the seafloor show that Jaeger's model of an infinitely conducting bar is only a poor model for a pipe model, still it does give a good idea of the behaviour of a cooling metal bar.

For the case of a probe in the shape of a pipe several considerations should be borne in mind. The first of these is that the initial rise in temperature of the probe will depend upon the material of the probe. The second is that a water filled pipe will cool more quickly than a sediment filled one.

The final choice of material for the probe depends more on the strength and corrosion effects of the marine environment, and possibly how long the probe can be left in the sediments before the temperatures are observed.

INTRODUCTION

This record presents the numerical results of Lee, Lewis and Liu (1991) for the numerical modelling of a marine heat probe in more detail than is possible in that paper. In addition to the tables for the fractional cooling of various probes, results are presented to indicate the accuracy of the calculations, and Jaeger's 1956 results for an infinitely conducting probe are cast in a form for ease of application and comparison, with the results for other models.

Previous studies of modelling of thermal probes rely heavily on the work of Jaeger (1940,1956) who considered the cooling/heating of a solid metal probe in a thermal environment. Practical use of these results has been made by Bullard (1954) and Lister (1979). More recently Haenel, Rybach and Stegena (1988) have further discussed the interpretation of heat flow data measured by a metal probe and have provided a table of values for the function which Jaeger had obtained in the form of an infinite integral of Bessel functions.

The above studies are deficient because they have not considered how a cylindrical or pipe model rather than a bar model might differ from one another. Composite cylinders, subjected to heating or cooling have been modelled mathematically. However such studies by Thiruvenkatachar (1952), Tranter (1947) and Jaeger (1941) are not appropriate for the case where the temperature at the outer cylinder can vary because of the temperature of surrounding medium which is assumed to be of infinite extent.

The work undertaken here considers the case of a more realistic model for a thermal probe, viz., a pipe. The thermal properties of the interior of the pipe, pipe and material outside the pipe may differ. It is assumed that the initial temperature of the pipe and material within the pipe were the same, but the initial temperature of the surrounding medium is, of course, different.

NUMERICAL RESULTS

The following tables present the results of our calculations for a variety of probe models and different situations.

Table 1 describes the various thermal properties of the materials, used to model a thermal probe in the ocean floor.

As can be seen, Jaeger's model of a perfectly conducting bar is a useful model for the thermal history of a cooling metal bar. For this reason Jaeger's (1956) table has been extended to produce a more detailed table, as is shown in table 2.

Table 3 gives some clue as to when Jaeger's model may be used, as it compares the results of a finite conductivity model against his infinite conductivity model. From this table one learns that, if one is only interested in how long it will take for the temperature to fall to a given percentage of its initial value, then Jaeger's approximations are adequate for most purposes.

In actual practice the thermal probe is not a solid bar but rather a metal cylinder and so the thermal behaviour of this model needs to be examined.

For this purpose a Fortran program was written to compute the fractional temperature of a pipe filled with various substances and embedded in the seafloor. Here the fractional temperature difference is devined to be the difference of the probe temperature, at time t, and the initial temperature of the sediment divided by the difference between the initial temperature of the sediment and the initial temperature of the probe. The results of the program were checked by filling the pipe with the same material as the pipe was made out of, so that the model reduced to a bar. The results could then be compared with an independent program which computed the thermal history of a bar. The results of this comparison are shown in table 4.

It is also important to compare the various thermal histories of different metal structures. This is done in table 5. This table shows that while Jaeger's model of an infinitely conducting bar might be used to model a finitely conducting metal bar, it is a poor approximation for modelling pipes. This table also shows that within reasonable practical values the wall thickness of the pipe is a critical factor in the probe design. One also sees that the temperature at a depth of three millimetres within a twenty millimetre radius bar, approximates that of the outside temperature. It is because of this that in future calculations of the thermal history of various pipe models, the temperature will be computed at the inside wall of the pipe.

As a thermal probe might be made from any one of several different metals, we have chosen to compare the results of our calculations for probes of different metals. This is done in table 6 which shows results for steel, copper, brass and aluminium probes. Table 7 repeats the comparison for the case where the probes are filled with water rather than sediment and table 8 shows the results of all the calculations.

These tables clearly show that at any specified time the fractional temperatures of different probes are different. A note of warning should be sounded here. Clearly one would like to choose a metal for the probe which gave the lowest fractional temperature at a given time. However, it should be borne in mind that the different materials which make up the models of table 8 have different specific heats. Accordingly those results should be corrected in a manner which reflects this observation. One way to do this is to assume that the same amount of heat is available to heat each probe and to calculate a factor which corrects for the initial temperature in each probe. A list of these factors is given in table 9. These factors are used to compute the results shown in tables 10 and 11.

Table 10 shows the results for the case of a solid bar. From this table one can make two observations, the first of which is that Jaeger's infinite conductivity model is a good approximation for a finitely conducting metal pipe. The second is that, once one allows for different initial temperature the choice of material for a bar model probe is not a critical one.

Table 11 shows a comparison of the various pipe models. Here the results are more complex. Firstly, one notices that in all cases a water filled pipe has a lower fractional temperature than a sediment filled one. Secondly one notices that it is far less obvious as to which metal should be used to manufacture the probe. As the relative differences are small, it would seem that the final choice of material would depend upon the strength and corrosion effects of the marine environment, and possibly how long the probe can be left in the sediments before the temperatures are observed.

As the pipe cooling tables are somewhat different from those for solid bars it seems preferable to calculate an appropriate table for whatever probe is used and to use these calculations for practical corrections rather than some other less applicable model.

TABLE 1

	Steel	Copper	Brass	Aluminium	Sediment	Water
Thermal Diffusivity	0.12	1.14	0.33	0.86	0.00829	0.00144
Thermal Conductivity	0.11	0.93	0.25	0.48	0.0021	0.00144
Jaeger´s ALPHA	0.559	0.623	0.676	0.918		

Thermal properties (in CGS units) as used in our calculations. Jaeger´s ALPHA is twice the product of the thermal conductivity of the sediment and the diffusivity of the probe divided by the product of the diffusivity of the sediment and the thermal conductivity of the probe. The sediment properties are the average of the five values determined by Von Herzen and Maxwell (1959). The other thermal properties are from Carslaw and Jaeger (1959, Appendix 6).

TABLE 2

ALPHA Time (s)	0.5	1.0	1.5	2.0	4.0	6.0	8.0
1	0.973	0.947	0.922	0.898	0.811	0.735	0.669
2	0.963	0.929	0.896	0.865	0.757	0.669	0.596
3	0.956	0.914	0.875	0.839	0.716	0.620	0.543
4	0.949	0.901	0.858	0.817	0.683	0.581	0.502
5	0.943	0.890	0.843	0.799	0.655	0.550	0.470
6	0.937	0.881	0.829	0.782	0.631	0.523	0.443
7	0.932	0.872	0.817	0.767	0.611	0.501	0.421
8	0.928	0.863	0.805	0.754	0.592	0.481	0.401
9	0.923	0.855	0.795	0.741	0.575	0.463	0.384
10	0.919	0.848	0.785	0.730	0.560	0.448	0.369
20	0.886	0.791	0.712	0.644	0.456	0.346	0.275
30	0.861	0.750	0.660	0.587	0.394	0.290	0.227
40	0.840	0.717	0.620	0.543	0.351	0.253	0.195
50	0.822	0.689	0.587	0.508	0.318	0.226	0.173
60	0.806	0.665	0.559	0.479	0.292	0.205	0.156
70	0.791	0.643	0.535	0.454	0.271	0.188	0.143
80	0.778	0.624	0.513	0.432	0.253	0.174	0.132
90	0.765	0.606	0.494	0.412	0.238	0.163	0.123
100	0.753	0.590	0.476	0.395	0.225	0.153	0.115
200	0.662	0.474	0.359	0.285	0.149	0.098	0.073
300	0.598	0.402	0.293	0.226	0.113	0.074	0.055
400	0.548	0.350	0.248	0.189	0.092	0.060	0.045
500	0.508	0.311	0.216	0.162	0.078	0.051	0.038
600	0.473	0.280	0.191	0.143	0.068	0.044	0.033
700	0.443	0.255	0.172	0.127	0.060	0.039	0.029
800	0.417	0.234	0.156	0.115	0.054	0.035	0.026
900	0.394	0.216	0.143	0.105	0.049	0.032	0.024
1000	0.374	0.201	0.132	0.096	0.045	0.029	0.022
2000	0.244	0.117	0.074	0.053	0.025	0.016	0.012
3000	0.178	0.081	0.051	0.037	0.018	0.011	0.009
4000	0.139	0.062	0.039	0.028	0.013	0.009	0.007
5000	0.113	0.050	0.032	0.023	0.011	0.007	0.005
6000	0.095	0.042	0.026	0.019	0.009	0.006	0.005
7000	0.081	0.036	0.023	0.017	0.008	0.005	0.004
8000	0.071	0.031	0.020	0.015	0.007	0.005	0.003
9000	0.063	0.028	0.018	0.013	0.006	0.004	0.003
10000	0.056	0.025	0.016	0.012	0.006	0.004	0.003
20000	0.027	0.012	0.008	0.006	0.003	0.002	0.001
30000	0.018	0.008	0.005	0.004	0.002	0.001	0.001
40000	0.013	0.006	0.004	0.003	0.001	0.001	0.001
50000	0.010	0.005	0.003	0.002	0.001	0.001	0.001
60000	0.008	0.004	0.003	0.002	0.001	0.001	0.000
70000	0.007	0.003	0.002	0.002	0.001	0.001	0.000
80000	0.006	0.003	0.002	0.002	0.001	0.000	0.000
90000	0.006	0.003	0.002	0.001	0.001	0.000	0.000
100000	0.005	0.002	0.002	0.001	0.001	0.000	0.000

Fractional residual temperatures for a perfectly conducting bar in a medium of finite conductivity. The parameter ALPHA is as defined by Jaeger (1956, p169).

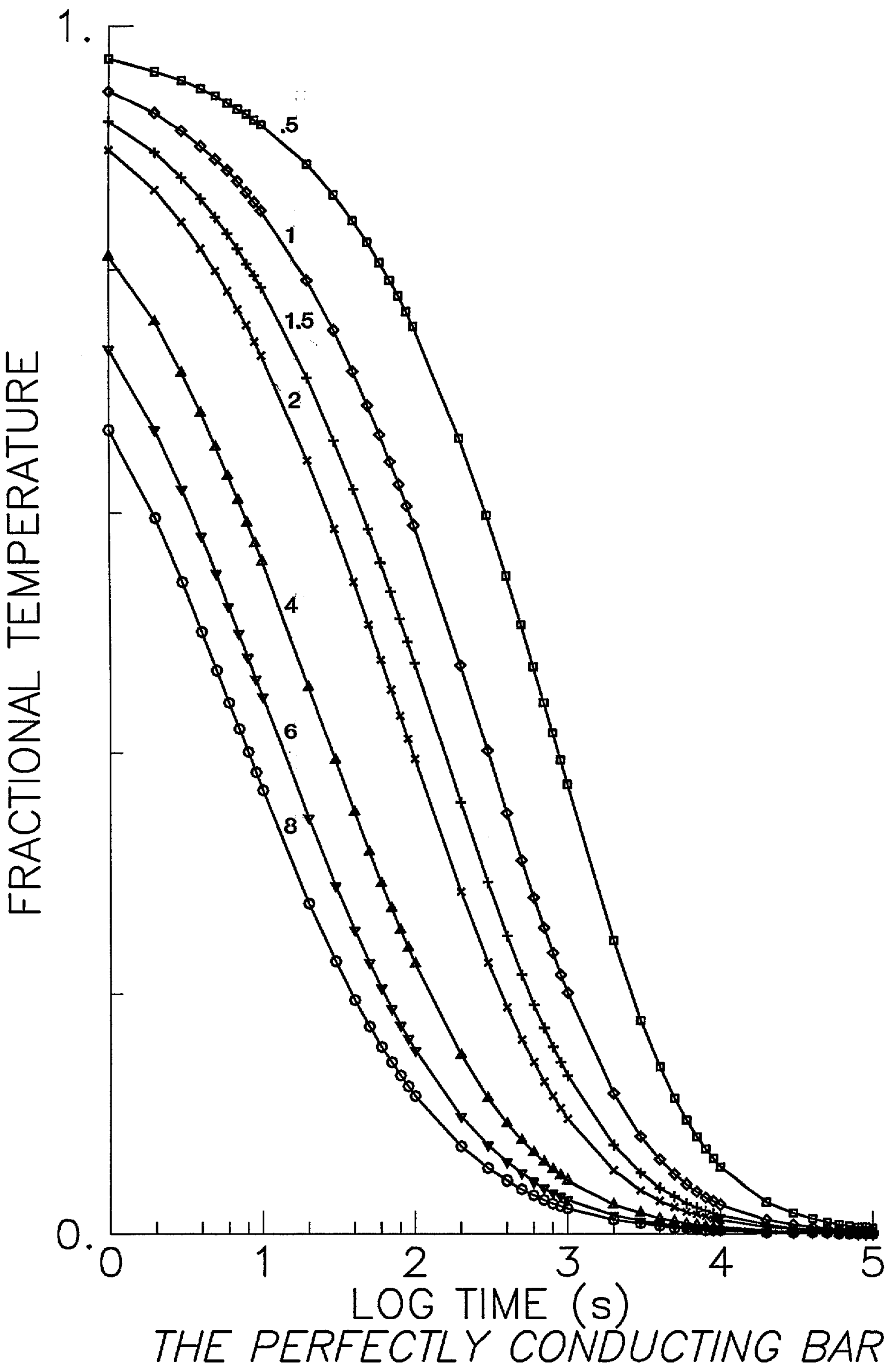

Figure 1.
Fractional residual temperatures for a perfectly conducting bar in a medium of finite conductivity. This is data from Table 2. The number on each curve is the parameter ALPHA as defined by Jaeger (1956, p169).

TABLE 3

Time (s)	Steel		Copper		Brass		Aluminium	
1	.970	.924	.967	.961	.964	.939	.951	.940
2	.959	.919	.955	.950	.951	.932	.934	.927
3	.950	.916	.945	.942	.941	.926	.921	.915
4	.943	.912	.937	.934	.932	.920	.909	.904
5	.936	.909	.929	.927	.924	.914	.899	.895
6	.930	.906	.923	.921	.917	.908	.889	.886
7	.925	.903	.917	.915	.910	.902	.881	.878
8	.920	.900	.911	.909	.904	.897	.873	.871
9	.915	.897	.906	.904	.898	.892	.866	.864
10	.910	.894	.901	.899	.893	.887	.859	.858
20	.874	.865	.861	.860	.851	.848	.806	.806
30	.847	.840	.832	.831	.819	.818	.767	.768
40	.824	.819	.807	.807	.793	.793	.735	.737
50	.805	.801	.786	.786	.771	.771	.709	.710
60	.787	.784	.767	.767	.751	.752	.685	.687
70	.771	.769	.750	.750	.734	.734	.664	.667
80	.757	.755	.735	.735	.717	.718	.645	.648
90	.743	.742	.720	.721	.702	.703	.628	.631
100	.730	.730	.707	.707	.688	.690	.612	.615
200	.634	.636	.606	.607	.584	.587	.498	.501
300	.568	.570	.537	.538	.514	.517	.426	.429
400	.517	.520	.485	.486	.462	.465	.374	.377
500	.475	.478	.444	.445	.420	.423	.334	.337
600	.441	.444	.409	.410	.386	.389	.302	.305
700	.411	.414	.380	.381	.357	.360	.276	.279
800	.385	.388	.354	.355	.332	.335	.254	.257
900	.362	.366	.332	.333	.310	.313	.235	.238
1000	.342	.346	.313	.314	.291	.294	.219	.221
2000	.218	.221	.195	.196	.179	.181	.128	.130
3000	.158	.160	.140	.140	.128	.129	.090	.091
4000	.122	.124	.108	.108	.098	.099	.069	.069
5000	.099	.101	.087	.088	.079	.080	.055	.056
6000	.083	.084	.073	.073	.066	.067	.046	.047
7000	.071	.072	.062	.063	.057	.057	.040	.040
8000	.062	.063	.055	.055	.049	.050	.035	.035
9000	.055	.056	.048	.048	.044	.044	.031	.031
10000	.049	.050	.043	.043	.039	.040	.028	.028
20000	.024	.024	.021	.021	.019	.019	.014	.014
30000	.015	.016	.014	.014	.013	.013	.009	.009
40000	.011	.012	.010	.010	.009	.009	.007	.007
50000	.009	.009	.008	.008	.007	.007	.005	.005
60000	.008	.008	.007	.007	.006	.006	.004	.005
70000	.006	.006	.006	.006	.005	.005	.004	.004
80000	.006	.006	.005	.005	.005	.005	.003	.003
90000	.005	.005	.004	.004	.004	.004	.003	.003
100000	.004	.004	.004	.004	.004	.004	.003	.003

A comparison of the fractional residual temperatures for 20mm radius solid bars as calculated by Jaeger's method (first column for each material) and using the finite conductivity model (second column).

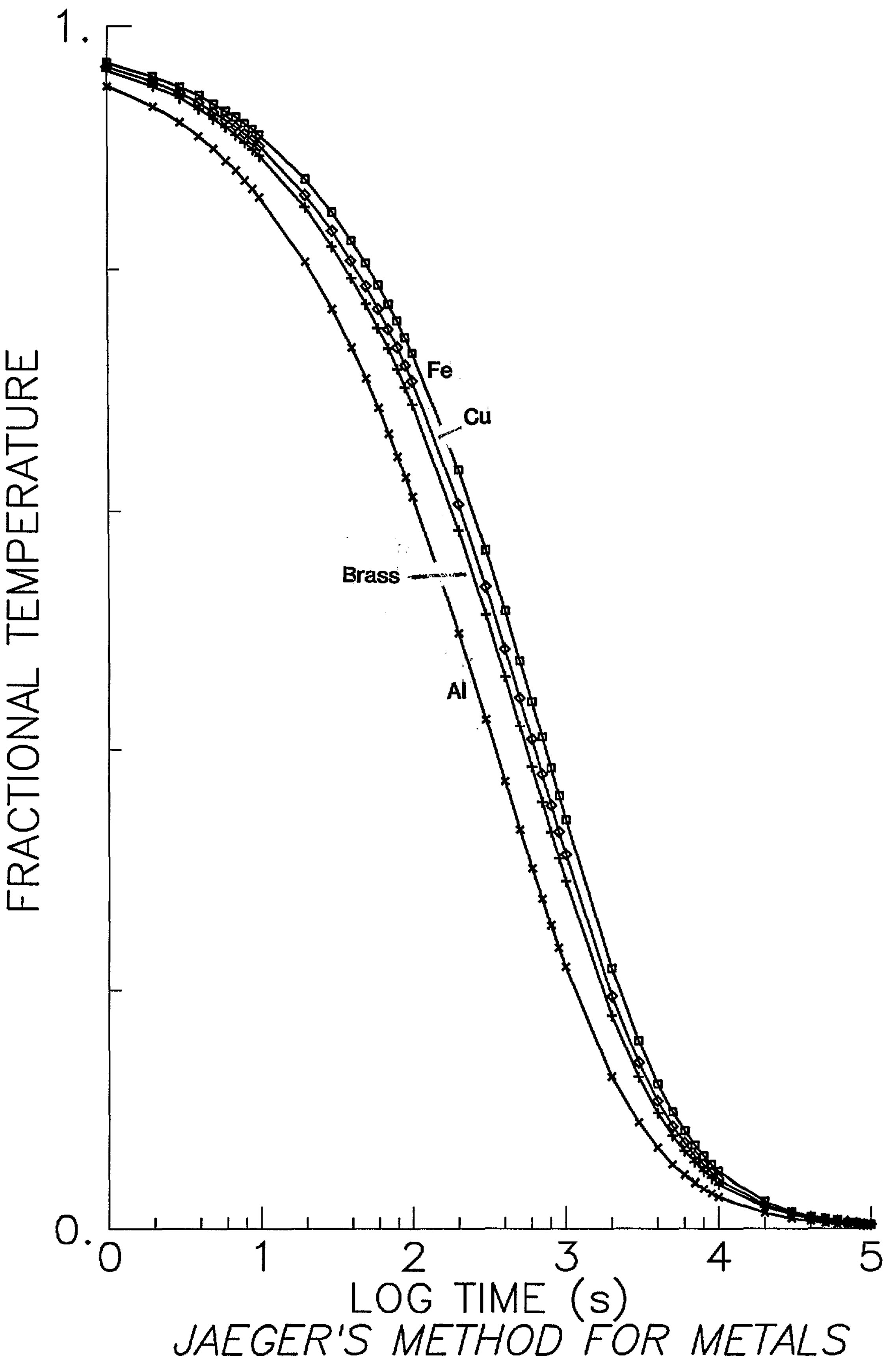

Figure 2.
The fractional residual temperatures for 20mm radius solid metal bars as calculated by Jaeger's method. Data is from Table 3.

TABLE 4

Time (s)	Pipe	Bar
1	.9236	.9236
2	.9194	.9194
3	.9158	.9158
4	.9125	.9125
5	.9093	.9093
6	.9061	.9061
7	.9030	.9030
8	.8998	.8998
9	.8967	.8967
10	.8936	.8936
20	.8646	.8646
30	.8403	.8403
40	.8194	.8194
50	.8010	.8010
60	.7843	.7843
70	.7692	.7692
80	.7551	.7551
90	.7421	.7421
100	.7299	.7299
200	.6359	.6359
300	.5703	.5703
400	.5196	.5196
500	.4784	.4784
600	.4439	.4439
700	.4142	.4142
800	.3885	.3885
900	.3658	.3658
1000	.3456	.3456
2000	.2210	.2210
3000	.1601	.1601
4000	.1242	.1242
5000	.1007	.1007
6000	.0843	.0843
7000	.0722	.0722
8000	.0630	.0630
9000	.0558	.0558
10000	.0500	.0500
20000	.0241	.0241
30000	.0157	.0157
40000	.0116	.0116
50000	.0092	.0092
60000	.0076	.0076
70000	.0065	.0065
80000	.0057	.0057
90000	.0050	.0050
100000	.0045	.0045

A test of the pipe calculations. The first column is for a 20mm radius steel pipe of wall thickness 10mm with a steel core. The second is for a solid steel bar. The calulations are from different programs and formulae. The agreement is acceptable.

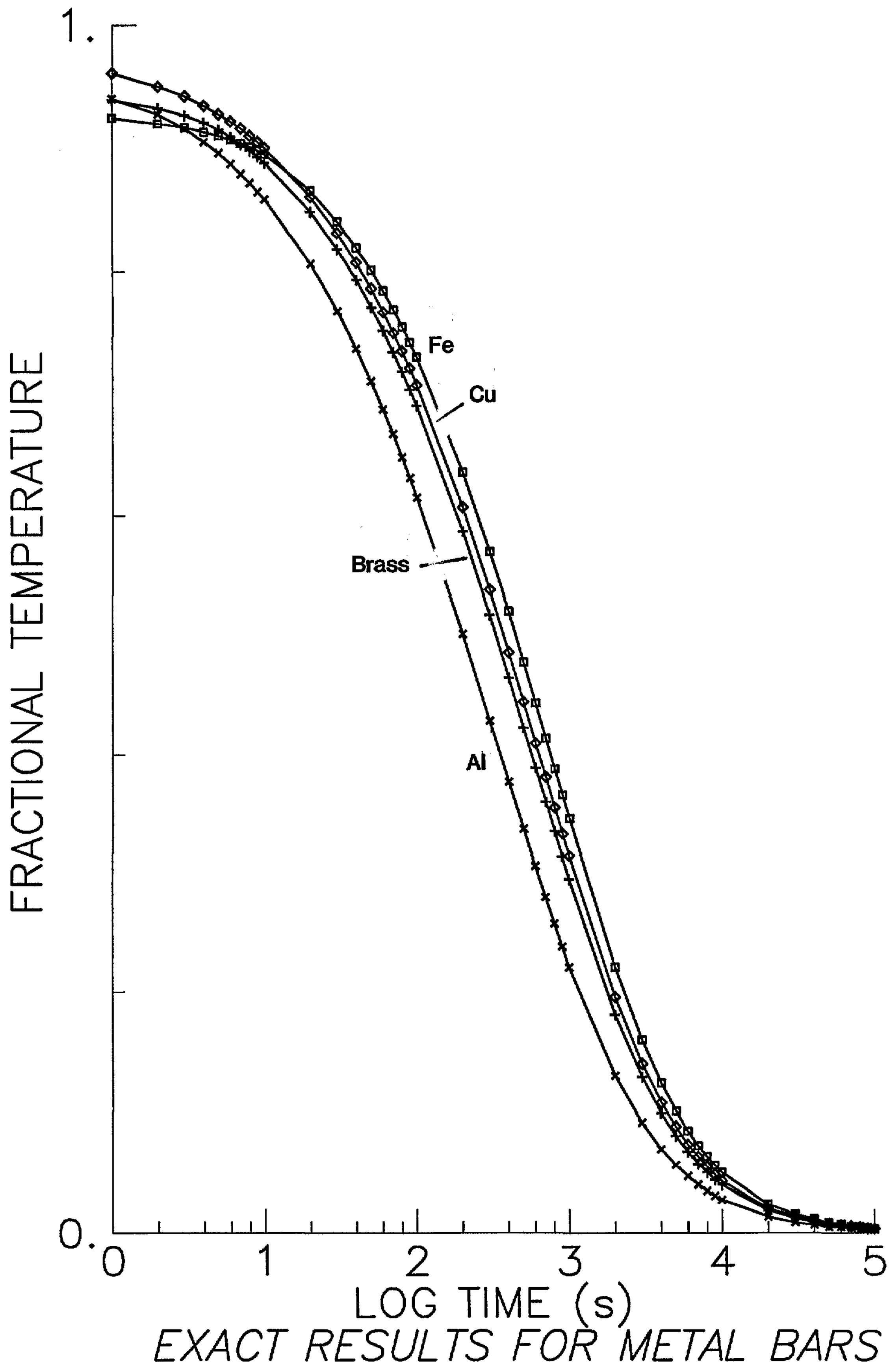

Figure 3.
The fractional residual temperatures for 20mm radius solid metal bars calculated by exact theory. Data is from Table 3.

TABLE 5

Time (s)	Jaeger	3mm	5mm	Bar	Bar-3mm
1	.970	.9177	.9546	.9236	.9563
2	.959	.8838	.9268	.9194	.9433
3	.950	.8602	.9082	.9158	.9355
4	.943	.8420	.8933	.9125	.9296
5	.936	.8264	.8812	.9093	.9246
6	.930	.8134	.8701	.9061	.9200
7	.925	.8016	.8606	.9030	.9158
8	.920	.7910	.8519	.8998	.9117
9	.915	.7815	.8439	.8967	.9078
10	.910	.7727	.8363	.8936	.9041
20	.874	.7103	.7807	.8646	.8718
30	.847	.6700	.7423	.8403	.8460
40	.824	.6396	.7126	.8194	.8243
50	.805	.6148	.6879	.8010	.8052
60	.787	.5943	.6666	.7843	.7882
70	.771	.5760	.6475	.7692	.7727
80	.757	.5597	.6304	.7551	.7584
90	.743	.5444	.6148	.7421	.7451
100	.730	.5307	.6004	.7299	.7327
200	.634	.4292	.4931	.6359	.6377
300	.568	.3622	.4227	.5703	.5717
400	.517	.3139	.3713	.5196	.5207
500	.475	.2774	.3314	.4784	.4793
600	.441	.2484	.2998	.4439	.4446
700	.411	.2249	.2736	.4142	.4149
800	.385	.2055	.2519	.3885	.3890
900	.362	.1891	.2328	.3658	.3663
1000	.342	.1750	.2169	.3456	.3460
2000	.218	.0997	.1267	.2210	.2212
3000	.158	.0692	.0886	.1601	.1602
4000	.122	.0525	.0677	.1242	.1242
5000	.099	.0426	.0544	.1007	.1007
6000	.083	.0354	.0453	.0843	.0843
7000	.071	.0304	.0388	.0722	.0722
8000	.062	.0266	.0342	.0630	.0630
9000	.055	.0236	.0304	.0558	.0558
10000	.049	.0213	.0270	.0500	.0500
20000	.024	.0107	.0133	.0241	.0241
30000	.015	.0072	.0088	.0157	.0157
40000	.011	.0053	.0065	.0116	.0116
50000	.009	.0042	.0053	.0092	.0092
60000	.008	.0034	.0046	.0076	.0076
70000	.006	.0030	.0038	.0065	.0065
80000	.006	.0027	.0034	.0057	.0057
90000	.005	.0023	.0030	.0050	.0050
100000	.004	.0023	.0027	.0045	.0045

A comparison of the fractional residual temperature of various steel structures and computational methods. The first column is the result of applying Jaeger's method. The next three columns are for 3mm, 5mm walled tubes and a solid bar. The last column is for a solid bar with the temperature measured 3mm within the outer surface. All structures are of steel with 20mm outer radius. The tubes are sediment filled.

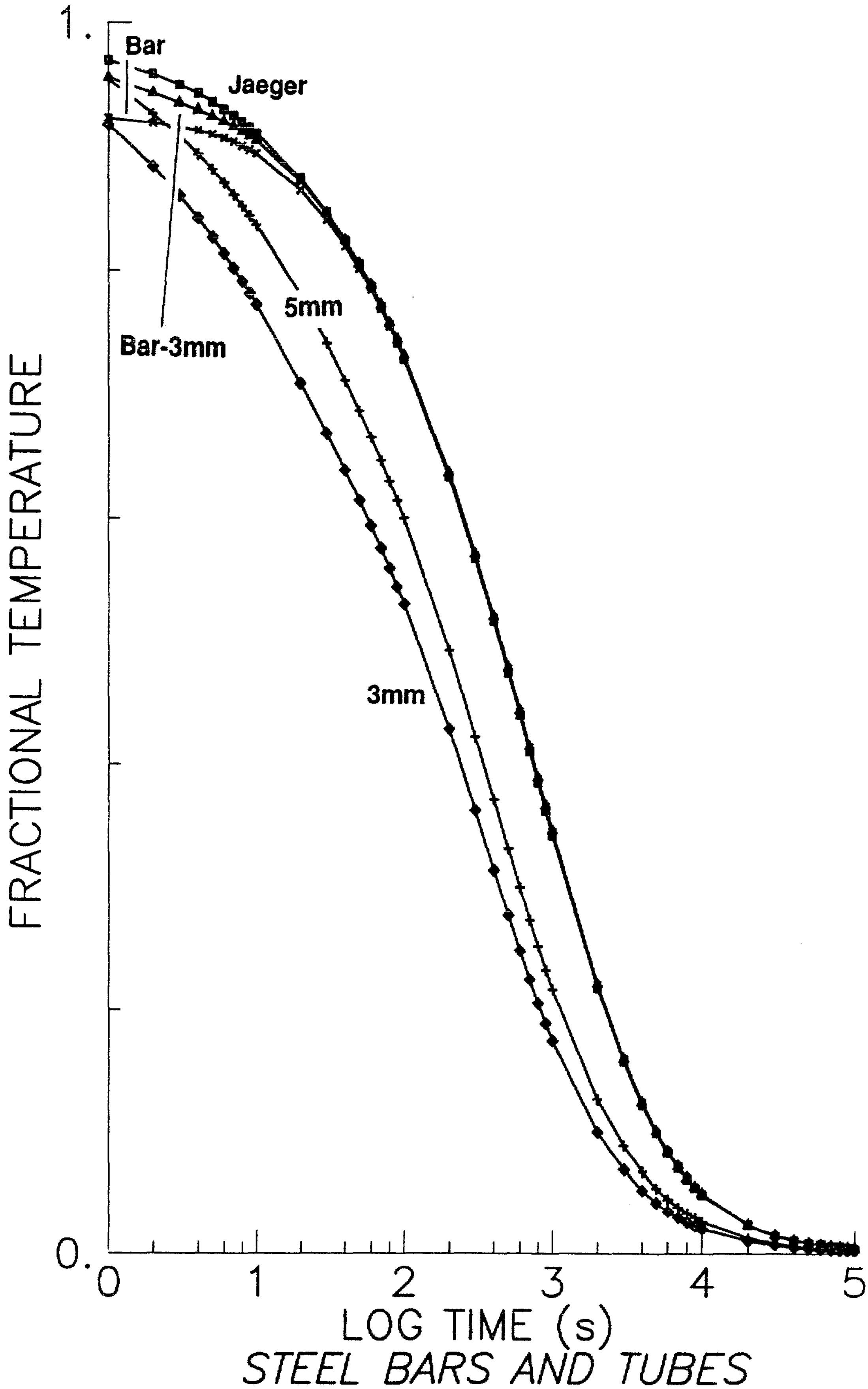

Figure 4.
Fractional temperature curves for various steel probes, both bars and tubes. See Table 5 for details of the probes.

TABLE 6

Time (s)	Steel	Copper	Brass	Aluminium
1	.9177	.9006	.8972	.8647
2	.8838	.8666	.8600	.8220
3	.8602	.8420	.8347	.7924
4	.8420	.8232	.8145	.7700
5	.8264	.8068	.7981	.7527
6	.8134	.7939	.7842	.7374
7	.8016	.7810	.7716	.7242
8	.7910	.7704	.7609	.7119
9	.7815	.7611	.7508	.7018
10	.7727	.7517	.7413	.6916
20	.7103	.6895	.6776	.6274
30	.6700	.6485	.6366	.5877
40	.6396	.6180	.6070	.5582
50	.6148	.5945	.5823	.5357
60	.5943	.5734	.5622	.5164
70	.5760	.5558	.5439	.4991
80	.5597	.5394	.5281	.4838
90	.5444	.5242	.5129	.4695
100	.5307	.5113	.4997	.4563
200	.4292	.4104	.4000	.3595
300	.3622	.3448	.3344	.2974
400	.3139	.2967	.2877	.2526
500	.2774	.2615	.2524	.2200
600	.2484	.2334	.2252	.1956
700	.2249	.2111	.2032	.1752
800	.2055	.1923	.1849	.1589
900	.1891	.1771	.1697	.1456
1000	.1750	.1630	.1571	.1344
2000	.0997	.0926	.0883	.0744
3000	.0692	.0645	.0612	.0519
4000	.0525	.0493	.0467	.0397
5000	.0426	.0399	.0379	.0316
6000	.0354	.0328	.0315	.0265
7000	.0304	.0281	.0271	.0224
8000	.0266	.0246	.0240	.0204
9000	.0236	.0223	.0208	.0183
10000	.0213	.0199	.0189	.0163
20000	.0107	.0094	.0095	.0081
30000	.0072	.0070	.0063	.0051
40000	.0053	.0047	.0044	.0041
50000	.0042	.0035	.0038	.0031
60000	.0034	.0035	.0032	.0031
70000	.0030	.0023	.0025	.0020
80000	.0027	.0023	.0025	.0020
90000	.0023	.0023	.0019	.0020
100000	.0023	.0023	.0019	.0020

Fractional residual temperature for 20mm radius tubes with 3mm wall thicknesses of various materials. The tube cavity is filled with sediment.

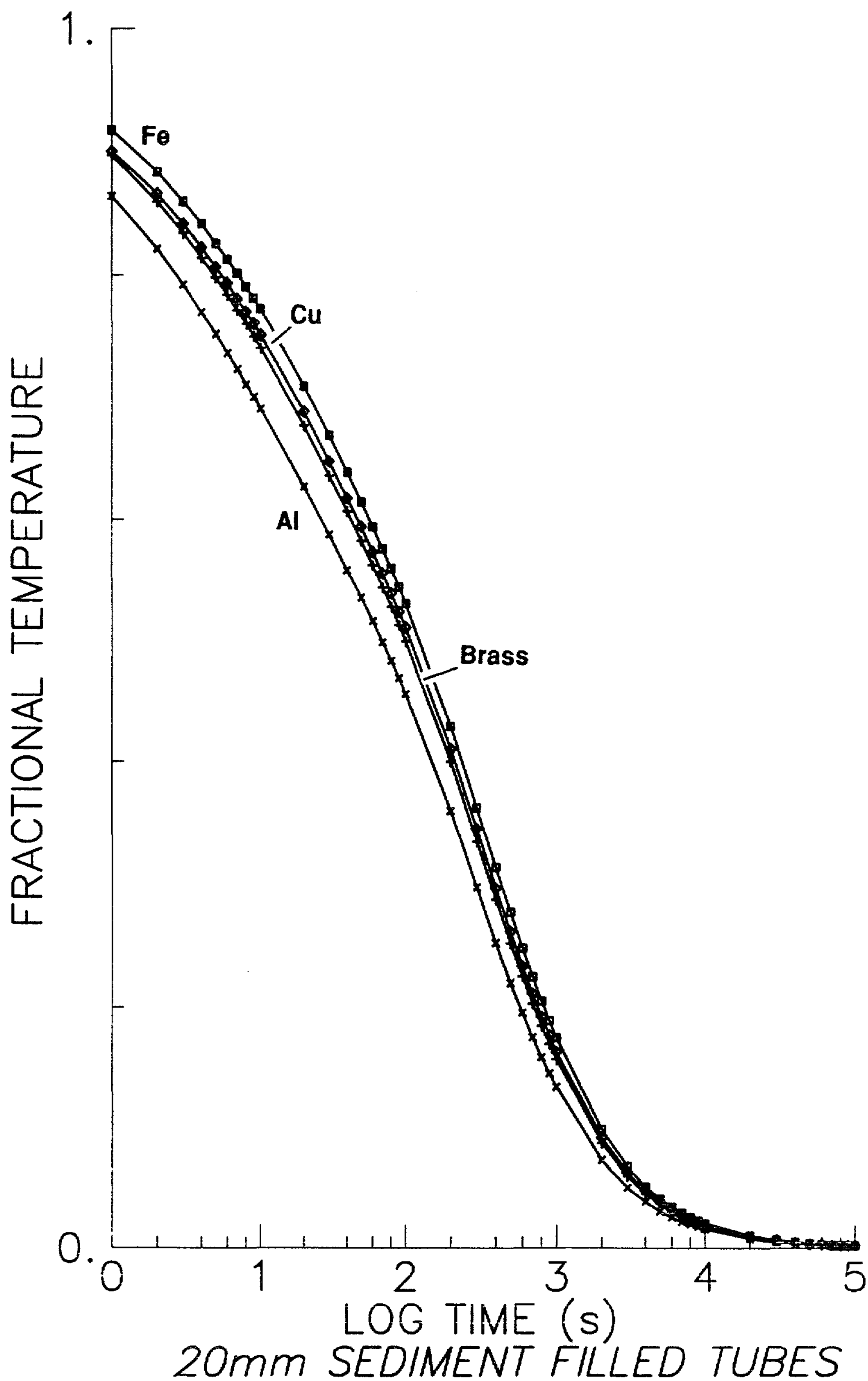

Figure 5.
Fractional residual temperature for 20mm radius tubes with 3mm wall thicknesses of various materials. The tube cavity is filled with sediment. Data from Table 6.

TABLE 7

Time (s)	Steel	Copper	Brass	Aluminium
1	.9220	.9060	.9053	.8724
2	.8900	.8750	.8720	.8358
3	.8691	.8525	.8493	.8113
4	.8535	.8357	.8326	.7942
5	.8398	.8244	.8190	.7796
6	.8289	.8131	.8069	.7674
7	.8188	.8019	.7963	.7551
8	.8106	.7935	.7857	.7478
9	.8024	.7850	.7766	.7405
10	.7951	.7794	.7705	.7331
20	.7458	.7287	.7206	.6843
30	.7157	.7006	.6918	.6574
40	.6938	.6781	.6706	.6378
50	.6755	.6612	.6540	.6232
60	.6618	.6471	.6403	.6110
70	.6491	.6359	.6282	.6012
80	.6381	.6246	.6176	.5914
90	.6290	.6162	.6086	.5816
100	.6198	.6077	.6010	.5743
200	.5605	.5487	.5435	.5230
300	.5212	.5121	.5056	.4863
400	.4902	.4811	.4753	.4594
500	.4637	.4558	.4496	.4326
600	.4391	.4305	.4269	.4106
700	.4181	.4108	.4057	.3886
800	.3980	.3883	.3860	.3690
900	.3798	.3714	.3663	.3519
1000	.3624	.3545	.3497	.3348
2000	.2437	.2363	.2331	.2199
3000	.1789	.1744	.1711	.1613
4000	.1397	.1351	.1317	.1246
5000	.1132	.1097	.1075	.1002
6000	.0940	.0900	.0893	.0831
7000	.0803	.0788	.0757	.0709
8000	.0703	.0675	.0666	.0611
9000	.0621	.0591	.0590	.0538
10000	.0557	.0535	.0530	.0489
20000	.0265	.0253	.0242	.0220
30000	.0173	.0169	.0167	.0147
40000	.0128	.0113	.0121	.0122
50000	.0100	.0084	.0091	.0098
60000	.0082	.0084	.0076	.0073
70000	.0073	.0056	.0061	.0073
80000	.0064	.0056	.0061	.0049
90000	.0055	.0056	.0045	.0049
100000	.0046	.0056	.0045	.0049

Fractional residual temperature for 20mm radius tubes with 3mm wall thicknesses of various materials. The tube cavity is filled with water.

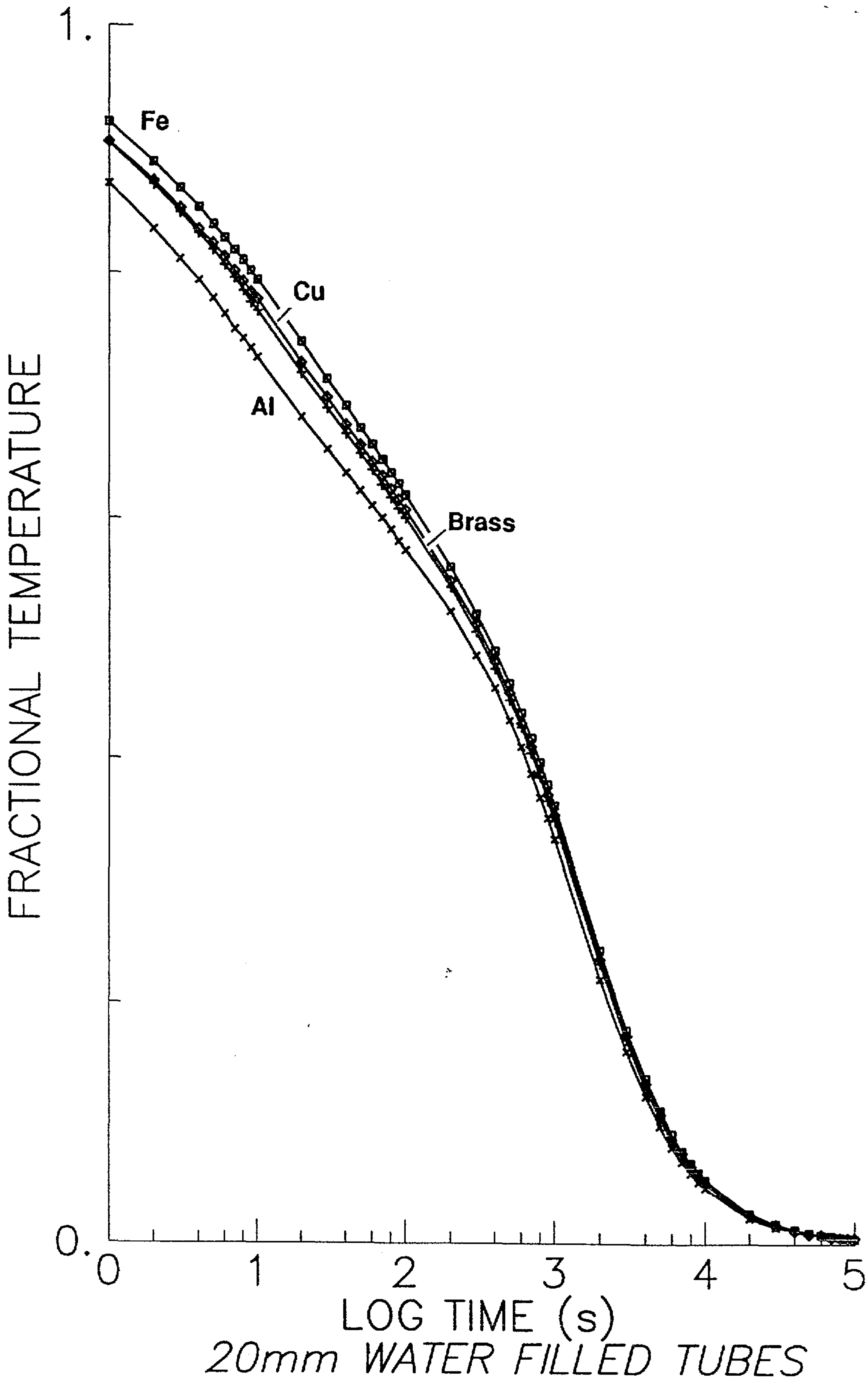

Figure 6.

Fractional residual temperature for 20mm radius tubes with 3mm wall thicknesses of various materials. The tube cavity is filled with water. Data from Table 7.

TABLE 8

Time (s)	Steel		Copper		Brass		Aluminium	
1	.9177	.9220	.9006	.9060	.8972	.9053	.8647	.8724
2	.8838	.8900	.8666	.8750	.8600	.8720	.8220	.8358
3	.8602	.8691	.8420	.8525	.8347	.8493	.7924	.8113
4	.8420	.8535	.8232	.8357	.8145	.8326	.7700	.7942
5	.8264	.8398	.8068	.8244	.7981	.8190	.7527	.7796
6	.8134	.8289	.7939	.8131	.7842	.8069	.7374	.7674
7	.8016	.8188	.7810	.8019	.7716	.7963	.7242	.7551
8	.7910	.8106	.7704	.7935	.7609	.7857	.7119	.7478
9	.7815	.8024	.7611	.7850	.7508	.7766	.7018	.7405
10	.7727	.7951	.7517	.7794	.7413	.7705	.6916	.7331
20	.7103	.7458	.6895	.7287	.6776	.7206	.6274	.6843
30	.6700	.7157	.6485	.7006	.6366	.6918	.5877	.6574
40	.6396	.6938	.6180	.6781	.6070	.6706	.5582	.6378
50	.6148	.6755	.5945	.6612	.5823	.6540	.5357	.6232
60	.5943	.6618	.5734	.6471	.5622	.6403	.5164	.6110
70	.5760	.6491	.5558	.6359	.5439	.6282	.4991	.6012
80	.5597	.6381	.5394	.6246	.5281	.6176	.4838	.5914
90	.5444	.6290	.5242	.6162	.5129	.6086	.4695	.5816
100	.5307	.6198	.5113	.6077	.4997	.6010	.4563	.5743
200	.4292	.5605	.4104	.5487	.4000	.5435	.3595	.5230
300	.3622	.5212	.3448	.5121	.3344	.5056	.2974	.4863
400	.3139	.4902	.2967	.4811	.2877	.4753	.2526	.4594
500	.2774	.4637	.2615	.4558	.2524	.4496	.2200	.4326
600	.2484	.4391	.2334	.4305	.2252	.4269	.1956	.4106
700	.2249	.4181	.2111	.4108	.2032	.4057	.1752	.3886
800	.2055	.3980	.1923	.3883	.1849	.3860	.1589	.3690
900	.1891	.3798	.1771	.3714	.1697	.3663	.1456	.3519
1000	.1750	.3624	.1630	.3545	.1571	.3497	.1344	.3348
2000	.0997	.2437	.0926	.2363	.0883	.2331	.0744	.2199
3000	.0692	.1789	.0645	.1744	.0612	.1711	.0519	.1613
4000	.0525	.1397	.0493	.1351	.0467	.1317	.0397	.1246
5000	.0426	.1132	.0399	.1097	.0379	.1075	.0316	.1002
6000	.0354	.0940	.0328	.0900	.0315	.0893	.0265	.0831
7000	.0304	.0803	.0281	.0788	.0271	.0757	.0224	.0709
8000	.0266	.0703	.0246	.0675	.0240	.0666	.0204	.0611
9000	.0236	.0621	.0223	.0591	.0208	.0590	.0183	.0538
10000	.0213	.0557	.0199	.0535	.0189	.0530	.0163	.0489
20000	.0107	.0265	.0094	.0253	.0095	.0242	.0081	.0220
30000	.0072	.0173	.0070	.0169	.0063	.0167	.0051	.0147
40000	.0053	.0128	.0047	.0113	.0044	.0121	.0041	.0122
50000	.0042	.0100	.0035	.0084	.0038	.0091	.0031	.0098
60000	.0034	.0082	.0035	.0084	.0032	.0076	.0031	.0073
70000	.0030	.0073	.0023	.0056	.0025	.0061	.0020	.0073
80000	.0027	.0064	.0023	.0056	.0025	.0061	.0020	.0049
90000	.0023	.0055	.0023	.0056	.0019	.0045	.0020	.0049
100000	.0023	.0046	.0023	.0056	.0019	.0045	.0020	.0049

A comparison of sediment and water filled 20mm radius tubes of 3mm wall thickness for various tube materials. The first column for each material is for a sediment filled tube, the second is for a water core.

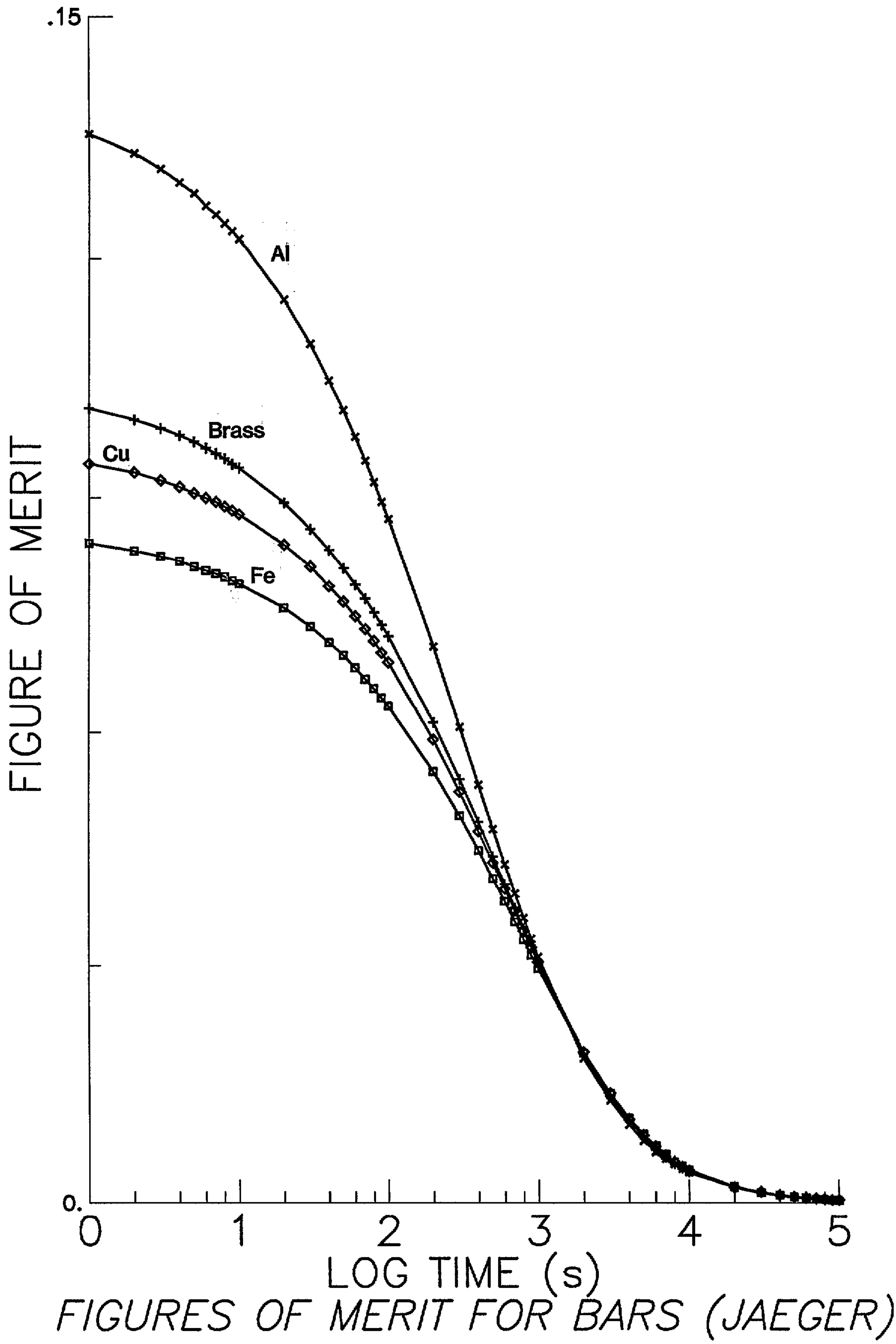

Figure 7.
Figures of merit for solid bar probes calculated using Jaeger's method. Data is from Table 10.

TABLE 9

Steel Bar	11.52
Copper Bar	10.25
Brass Bar	9.520
Aluminium Bar	7.014
Steel Pipe, 3mm Wall, Water Core	12.28
Copper Pipe, 3mm Wall, Water Core	11.92
Brass Pipe, 3mm Wall, Water Core	11.72
Aluminium Pipe, 3mm Wall, Water Core	11.03
Steel Pipe, 5mm Wall, Sediment Core	6.830
Steel Pipe, 3mm Wall, Sediment Core	5.496
Copper Pipe, 3mm Wall, Sediment Core	5.145
Brass Pipe, 3mm Wall, Sediment Core	4.942
Aluminium Pipe, 3mm Wall, Sediment Core	4.246

Factors for the initial temperature rise of a probe assuming the same frictional heating for each case. All probes are 20mm external radius.

TABLE 10

Time (s)	Steel		Copper		Brass		Aluminium	
1	.0842	.0802	.0943	.0937	.1013	.0986	.1356	.1340
2	.0832	.0798	.0932	.0927	.0999	.0979	.1332	.1321
3	.0825	.0795	.0922	.0919	.0988	.0973	.1313	.1304
4	.0819	.0792	.0914	.0911	.0979	.0966	.1296	.1289
5	.0812	.0789	.0906	.0904	.0971	.0960	.1282	.1276
6	.0807	.0787	.0900	.0898	.0963	.0954	.1267	.1264
7	.0803	.0784	.0895	.0892	.0956	.0948	.1256	.1252
8	.0799	.0781	.0889	.0887	.0950	.0942	.1245	.1242
9	.0794	.0778	.0884	.0882	.0943	.0937	.1235	.1232
10	.0790	.0776	.0879	.0877	.0938	.0932	.1225	.1223
20	.0759	.0751	.0840	.0840	.0894	.0891	.1149	.1149
30	.0735	.0729	.0812	.0811	.0860	.0859	.1094	.1095
40	.0715	.0711	.0787	.0787	.0833	.0833	.1048	.1050
50	.0699	.0695	.0767	.0767	.0810	.0810	.1011	.1013
60	.0683	.0681	.0748	.0749	.0789	.0790	.0977	.0980
70	.0669	.0668	.0732	.0732	.0771	.0771	.0947	.0950
80	.0657	.0656	.0717	.0717	.0753	.0754	.0920	.0924
90	.0645	.0644	.0702	.0703	.0737	.0739	.0895	.0899
100	.0634	.0634	.0690	.0690	.0723	.0724	.0873	.0877
200	.0550	.0552	.0591	.0592	.0613	.0616	.0710	.0715
300	.0493	.0495	.0524	.0525	.0540	.0543	.0607	.0612
400	.0449	.0451	.0473	.0474	.0485	.0488	.0533	.0538
500	.0412	.0415	.0433	.0434	.0441	.0444	.0476	.0481
600	.0383	.0385	.0399	.0400	.0405	.0408	.0431	.0435
700	.0357	.0360	.0371	.0371	.0375	.0378	.0393	.0397
800	.0334	.0337	.0345	.0347	.0349	.0352	.0362	.0366
900	.0314	.0318	.0324	.0325	.0326	.0329	.0335	.0339
1000	.0297	.0300	.0305	.0306	.0306	.0309	.0312	.0316
2000	.0189	.0192	.0190	.0191	.0188	.0190	.0182	.0185
3000	.0137	.0139	.0137	.0137	.0134	.0136	.0128	.0130
4000	.0106	.0108	.0105	.0106	.0103	.0104	.0098	.0099
5000	.0086	.0087	.0085	.0085	.0083	.0084	.0078	.0080
6000	.0072	.0073	.0071	.0071	.0069	.0070	.0066	.0067
7000	.0062	.0063	.0060	.0061	.0060	.0060	.0057	.0057
8000	.0054	.0055	.0054	.0053	.0051	.0053	.0050	.0050
9000	.0048	.0048	.0047	.0047	.0046	.0047	.0044	.0044
10000	.0043	.0043	.0042	.0042	.0041	.0042	.0040	.0040
20000	.0021	.0021	.0020	.0021	.0020	.0020	.0020	.0020
30000	.0013	.0014	.0014	.0013	.0014	.0013	.0013	.0013
40000	.0010	.0010	.0010	.0010	.0009	.0010	.0010	.0010
50000	.0008	.0008	.0008	.0008	.0007	.0008	.0007	.0008
60000	.0007	.0007	.0007	.0007	.0006	.0007	.0006	.0006
70000	.0005	.0006	.0006	.0006	.0005	.0006	.0006	.0005
80000	.0005	.0005	.0005	.0005	.0005	.0005	.0004	.0005
90000	.0004	.0004	.0004	.0004	.0004	.0004	.0004	.0004
100000	.0003	.0004	.0004	.0004	.0004	.0004	.0004	.0004

A comparison of figures of merit for 20mm radius solid bar probes. The figure of merit is the fractional residual temperature divided by the initial temperature coefficient. The smaller the figure of merit the better the probe cools. The first column for each metal assumes Jaeger's method, the second the finite conductivity bar.

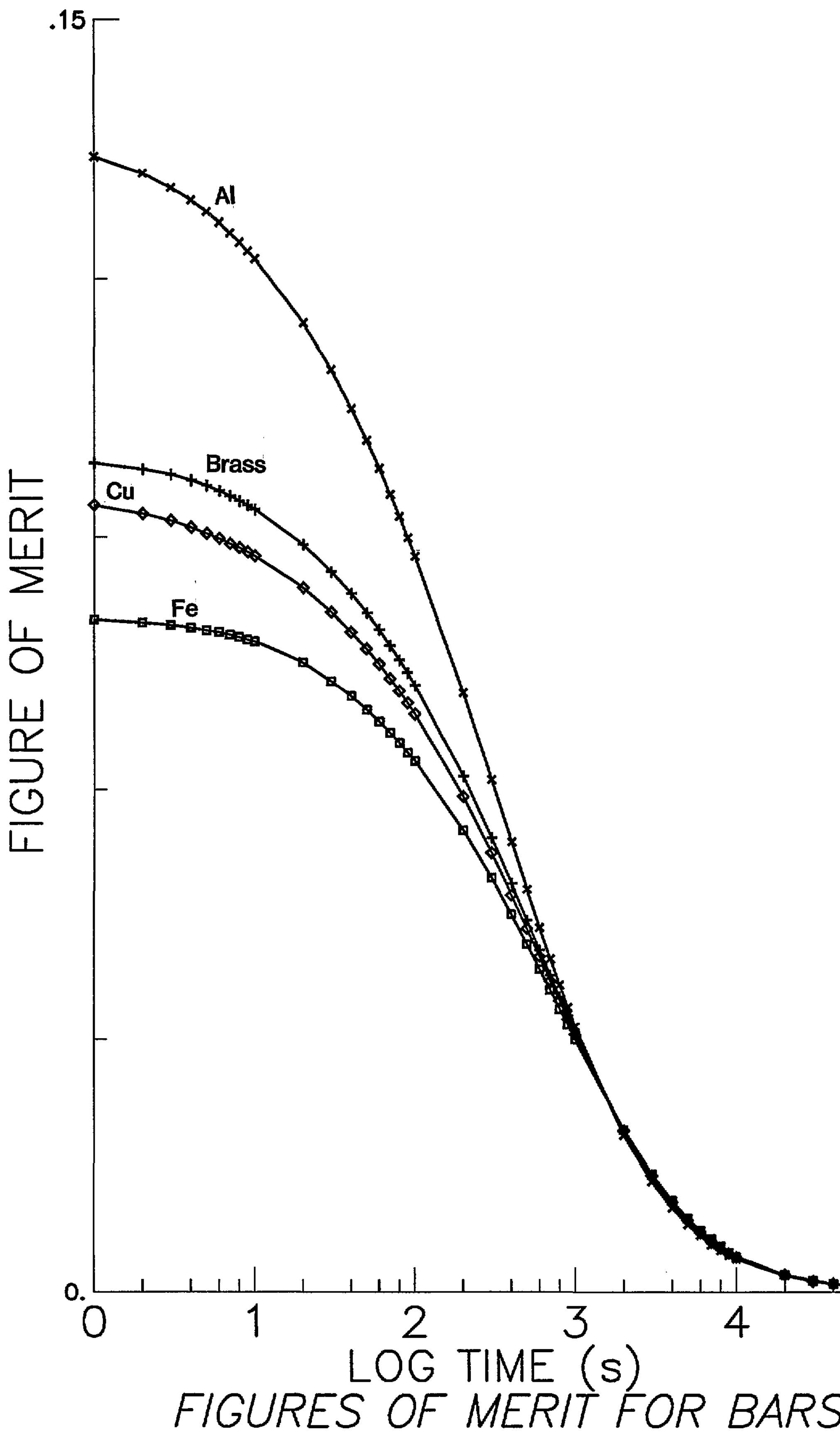

Figure 8.
Figures of merit for solid bar probes using exact theory. Data is from Table 10.

TABLE 11

Time (s)	Steel		Copper		Brass		Aluminium	
1	.16697	.07508	.17504	.07599	.18154	.07723	.20365	.07910
2	.16081	.07248	.16843	.07340	.17401	.07440	.19358	.07578
3	.15651	.07076	.16364	.07152	.16890	.07246	.18662	.07355
4	.15319	.06950	.15999	.07011	.16481	.07104	.18134	.07201
5	.15035	.06839	.15680	.06916	.16149	.06987	.17727	.07067
6	.14800	.06749	.15430	.06820	.15869	.06884	.17366	.06957
7	.14585	.06668	.15180	.06727	.15613	.06794	.17055	.06845
8	.14392	.06601	.14975	.06657	.15396	.06703	.16768	.06779
9	.14219	.06534	.14792	.06586	.15192	.06626	.16527	.06713
10	.14059	.06475	.14610	.06538	.15000	.06574	.16288	.06647
20	.12924	.06073	.13402	.06114	.13711	.06147	.14776	.06204
30	.12190	.05827	.12603	.05877	.12881	.05902	.13840	.05960
40	.11636	.05649	.12011	.05689	.12281	.05722	.13145	.05782
50	.11186	.05501	.11555	.05545	.11783	.05580	.12617	.05650
60	.10813	.05389	.11145	.05430	.11375	.05463	.12162	.05540
70	.10480	.05285	.10803	.05334	.11004	.05360	.11753	.05449
80	.10183	.05196	.10484	.05239	.10685	.05269	.11394	.05361
90	.09906	.05122	.10188	.05168	.10379	.05192	.11058	.05273
100	.09656	.05047	.09937	.05098	.10111	.05127	.10746	.05207
200	.07808	.04564	.07977	.04603	.08094	.04636	.08468	.04741
300	.06590	.04244	.06700	.04296	.06766	.04314	.07004	.04408
400	.05711	.03992	.05766	.04037	.05821	.04055	.05949	.04164
500	.05046	.03776	.05082	.03823	.05106	.03836	.05181	.03922
600	.04520	.03575	.04535	.03612	.04557	.03642	.04605	.03721
700	.04091	.03405	.04103	.03446	.04111	.03462	.04126	.03524
800	.03738	.03240	.03738	.03258	.03740	.03294	.03742	.03345
900	.03440	.03092	.03441	.03114	.03434	.03126	.03430	.03191
1000	.03184	.02951	.03168	.02974	.03178	.02983	.03166	.03035
2000	.01813	.01984	.01800	.01983	.01787	.01989	.01750	.01994
3000	.01259	.01456	.01253	.01463	.01238	.01459	.01223	.01461
4000	.00955	.01137	.00956	.01133	.00944	.01123	.00936	.01129
5000	.00775	.00922	.00775	.00920	.00765	.00917	.00743	.00909
6000	.00643	.00765	.00637	.00754	.00638	.00761	.00623	.00752
7000	.00554	.00654	.00546	.00661	.00548	.00646	.00527	.00642
8000	.00484	.00572	.00478	.00565	.00485	.00567	.00479	.00554
9000	.00429	.00505	.00432	.00495	.00421	.00504	.00431	.00486
10000	.00387	.00453	.00387	.00447	.00383	.00452	.00384	.00442
20000	.00193	.00215	.00181	.00213	.00191	.00207	.00191	.00200
30000	.00131	.00141	.00137	.00140	.00127	.00142	.00120	.00132
40000	.00097	.00104	.00091	.00095	.00089	.00102	.00095	.00110
50000	.00076	.00082	.00068	.00070	.00076	.00077	.00072	.00088
60000	.00062	.00066	.00068	.00070	.00063	.00065	.00072	.00066
70000	.00055	.00059	.00045	.00047	.00051	.00051	.00047	.00066
80000	.00048	.00052	.00045	.00047	.00051	.00051	.00047	.00044
90000	.00041	.00044	.00045	.00047	.00038	.00039	.00047	.00044
100000	.00041	.00037	.00045	.00047	.00038	.00039	.00047	.00044

A comparison of the figures of merit for sediment and water filled 20mm radius tubes of 3mm wall thickness for various tube materials. The first column for each material is for a sediment filled tube, the second is for a water core.

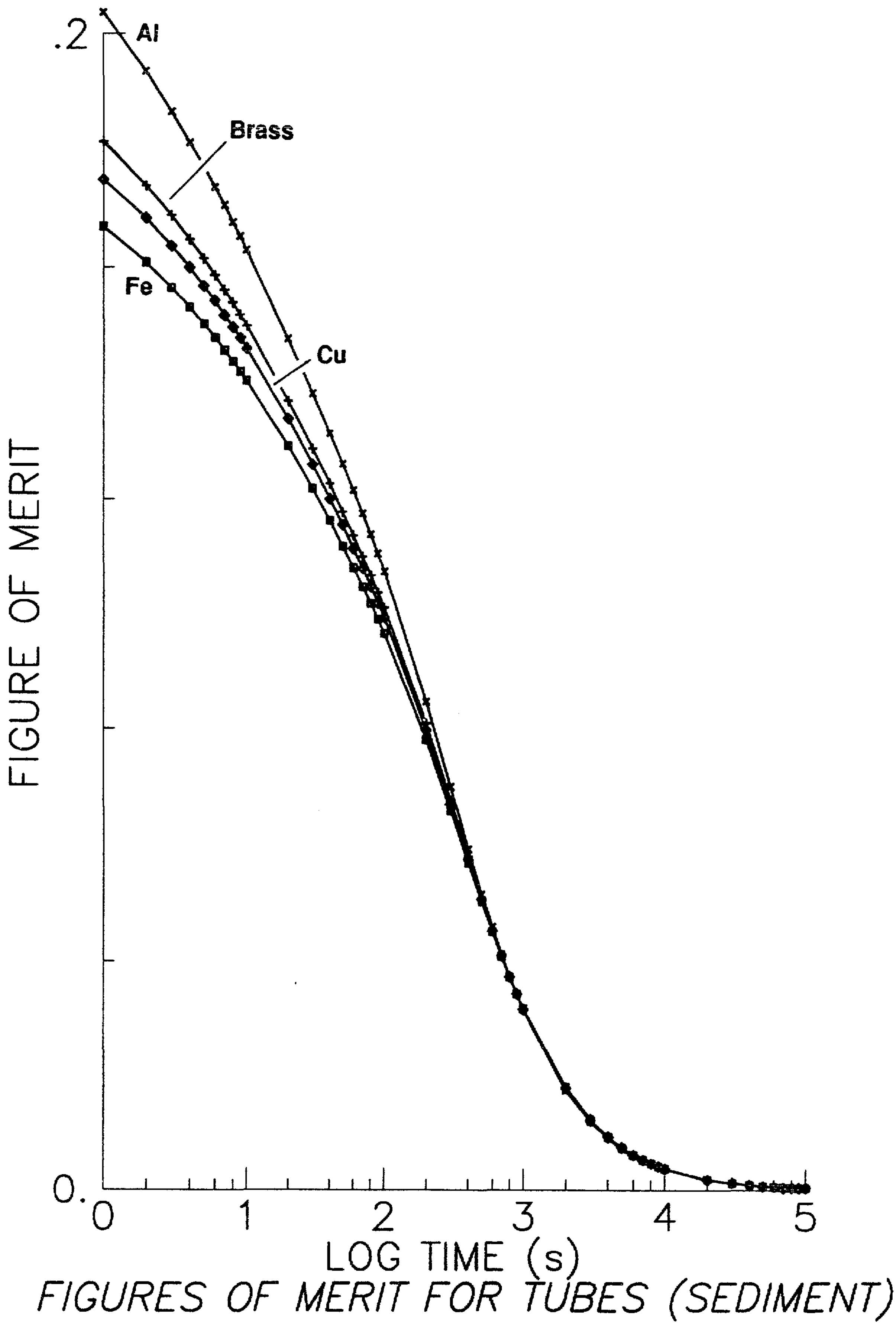

Figure 9.
Figures of merit for 20mm radius 3mm wall thickness tubular probes filled with sediment. Data is from Table 11.

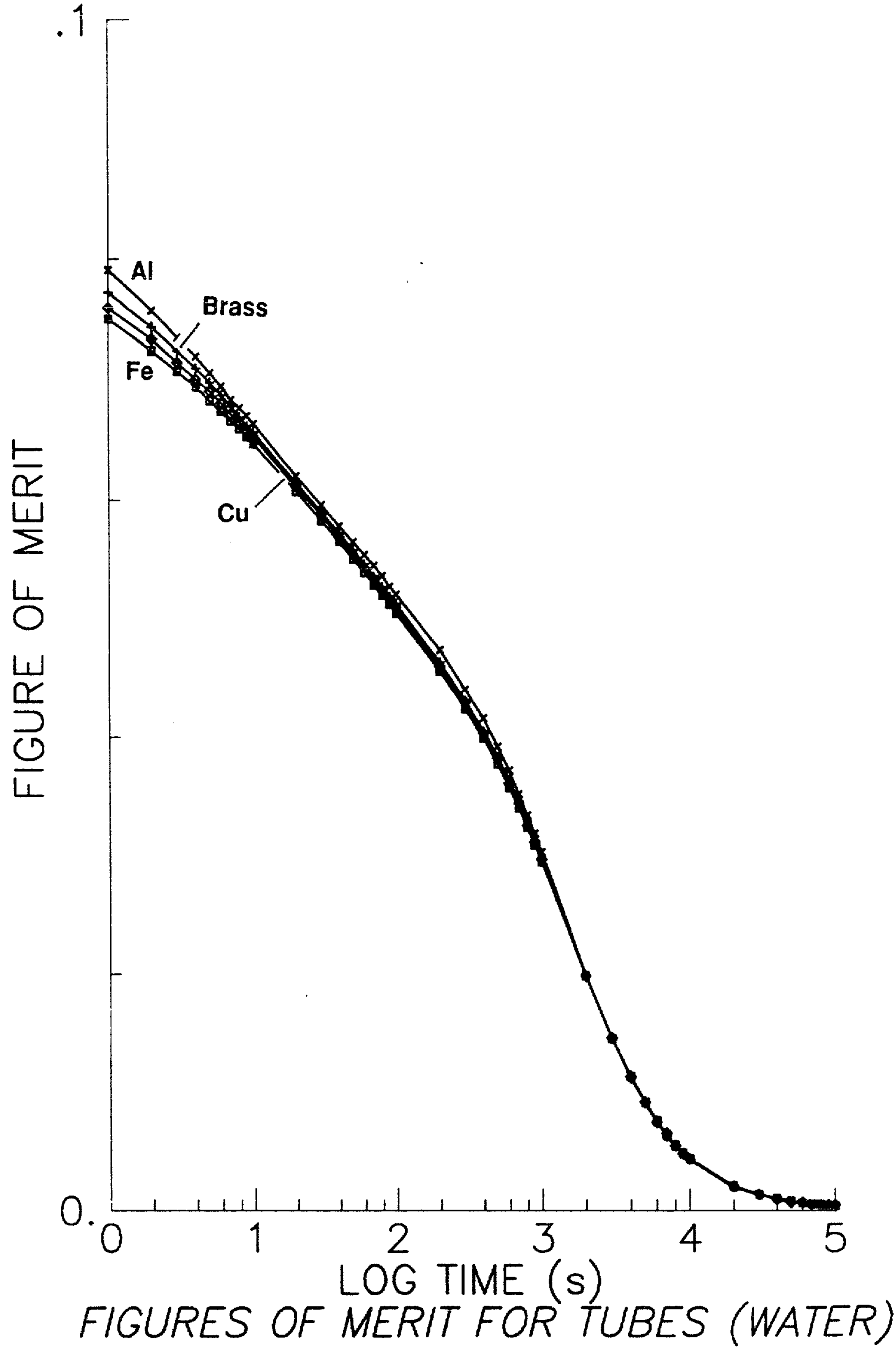

Figure 10.
Figures of merit for 20mm radius 3mm wall thickness tubular probes filled with water. Data is from Table 11.

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