An Experimental Examination of the IAEA Fire Test Parameters

C.J. Fry

AEA Technology, Winfrith Technology Centre, Dorchester, Dorset, England

INTRODUCTION

Pool fire tests have been performed at Winfrith Technology Centre for a number of years both to test containers for transporting radioactive materials, as specified in the IAEA regulations (IAEA 1985), and for performing basic scientific studies. This paper presents the results of the most recent series of scientific tests in which seven pool fire tests were carried out on two cubic test containers. The purpose of this series of tests was:

1. To measure the heat fluxes absorbed into a plain (ie unfinned) surface of a container in a pool fire test.
2. To measure flame temperatures and radiative heat fluxes in a pool fire test.
3. To compare the absorbed heat fluxes against that predicted from the measured radiative heat fluxes and flame temperatures.
4. To determine how the magnitude and uniformity of the heat flux into the different sides of the test container varies with the height of the vessel above the pool of fuel and the size of the fuel pool.
5. To compare these results against the prescription of a pool fire test given in the IAEA regulations and make suggestions for any possible improvements in the prescription.

The first six tests were performed upon a cubic test vessel constructed from six thick steel plates. The tests were therefore named the Thick Slab Vessel (TSV) test series. Each steel plate acted as a calorimeter, the absorbed heat flux being derived from the rate at which it heated up. The final test was performed upon a thin-walled vessel of the same shape and dimensions. This test was performed in order to study the effect of the thermal capacity of the vessel itself upon the measured flame temperatures and heat fluxes.

DESCRIPTION OF THE TESTS

The seven Thick Slab Vessel fire tests were carried out between March 1989 and October 1991. The first four tests were identical except for the vessel height which varied from 0.4 m to 1.0 m above the pool. The next two tests investigated the effect of pool size which was varied from 1 m to 3 m beyond the vessel on each side. The final test repeated the conditions of one of the earlier tests but with the thin-walled vessel. The conditions of each of the tests are listed in Table 1.

The Thick Slab Vessel was cube shaped of side 1.092 m and was constructed from 89 mm thick slabs of mild steel. The steel slabs were insulated on the inside and around their edges. The front face of each slab was initially painted with a high temperature white paint of known emissivity. However, a fine layer of black soot was deposited early in the first test which was very difficult to remove and therefore remained on the vessel surface at the start of subsequent tests. The vessel was mounted on a three-legged stand. The legs of this stand had a removable section to enable the height of the vessel to be varied and were water-cooled. Flame guides consisting of thin steel panels, in a cross formation, were mounted vertically below the vessel. In a previous test series this arrangement had been shown to reduce the natural non-uniformity of the flame cover.

Each slab of the vessel was instrumented with 6 thermocouples, 5 close to the front face and one in the centre of the back face. Those near the front face were positioned 1 mm below the surface in order to eliminate measurement errors which could arise from the heat flux from the fire being directly incident upon them; one was located in the centre and one 338 mm in from each corner along the diagonal. Two Directional Flame Thermometers (DFTs) were mounted on each face of the vessel to measure the incident radiation flux. DFTs are flame thermometers which have been designed and developed at Winfrith especially for use in pool fires. They have been described previously (Fry 1989 and Burgess & Fry 1990). Further DFTs were also mounted, facing outwards, 0.5 m, 1.0 m and 1.5 m from each side of the vessel. The temperatures measured by all these instruments, plus the local wind speed and direction, were recorded on a data logger every 15 seconds.

TEST	VESSEL TYPE	HEIGHT ABOVE POOL (m)	FUEL BUND		WIND CONDITIONS	
			WIDTH (m)	LENGTH (m)	SPEED (m/s)	DIRECTION (FROM)
1	THICK	1.0	5.0	5.3	1-2	EAST
2	THICK	0.8	5.0	5.3	½-1½	EAST
3	THICK	0.6	5.0	5.3	½-2	NORTH
4	THICK	0.4	5.0	5.3	0-1.0	EAST
5	THICK	1.0	3.1	3.1	2-2½	SOUTH-EAST
6	THICK	1.0	6.5	7.1	2½-3½	SOUTH-EAST
7	THIN	1.0	5.1	5.1	0-1	EAST

TABLE 1. TEST CONDITIONS

The thin-walled vessel was also cube shaped of side 1.092 m and was constructed from 2 mm thick mild steel plates. It was instrumented with two DFTs on each of its six faces, in identical locations to those on the Thick Slab Vessel, plus one thermocouple attached, in the centre, to the back of each face.

The size of a pool fire in the Pool Fire Test Facility is governed by a steel bund which retains the fuel. The size of bund in each test is shown in Table 1. In most of the tests pool size was approximately 5 m square giving a total fuel area of 25m^2. In each test a depth of typically 75 mm of fuel (Kerosene) was used, sufficient to burn for about 15 minutes. The fuel was floated on water and the water depth was controlled to give the desired height between the fuel surface and the bottom of the vessel.

It was endeavoured to perform all the tests on calm days. However, a slight breeze still existed in most cases. The magnitude of this wind and its direction varied from test to test and this has to be taken into account when comparing results from the different tests.

GENERAL OBSERVATIONS

All the fires appeared to be generally similar. The flames 'necked in' from the edges of the pool so that, at the height of the test vessel, the flame cover was typically less than 1 m. This behaviour is typical of any pool fire. At the elevated temperatures in a pool fire the strength of steel is greatly diminished. The Thick Slab Vessel and is stand, which had water-cooled legs, remained undamaged throughout the whole test series.

The heat flux into each face of the vessel, as a function of time, was calculated from its measured temperature using the SODDIT inverse conduction code (Blackwell et al. 1987). A typical calculated heat flux, as a function of time, is shown in Figure 1. It is immediately apparent that large variations in heat flux occur with time and significant variations also were observed from face to face. This reflects the changes in flame cover, caused primarily by the wind, which occur during the test. The absorbed heat fluxes did not noticeably drop off with time as the vessel heated up. This demonstrates that, even at the end of the test, the steel slabs of the vessel were still sufficiently cool for the heat radiated from their surfaces to be insignificant compared to the incident radiation.

THE EFFECT OF VESSEL HEIGHT

The average heat flux into each of the faces of the Thick Slab Vessel during tests TSV-1 to TSV-4 can be seen in Figure 2. These tests were all identical except for the height of the vessel above the fuel which varied from 0.4 m to 1.0 m. A solid vertical line has been drawn for each test showing the range of average heat fluxes into the sides of the vessel. The heat fluxes into the top and bottom faces are just shown as points.

The uniformity of the heat flux into the sides of the vessel appears to improve slightly as the height of the vessel above the fuel is reduced. This is due to a low vessel being less susceptible to the effects of wind. The magnitude of the average heat flux into the sides of the vessel decreases slightly as the vessel height is reduced down to 0.6 m but then increases again rapidly at 0.4 m. This may be due to the effective flame thickness round the vessel being greater when the vessel is low down. It is possible, however, that some of the observed variations are due to the different wind conditions during the tests. This could only be proved by performing a number of tests under identical conditions. From these results it is concluded that the effect of the vessel height upon the heat flux into the sides of the vessel is not very significant.

With the vessel 1 m above the fuel the heat flux into the bottom face is similar to that into the vessel sides. However, the heat flux into the top of the vessel is slightly less than that into the vessel sides and base. A similar picture of heat fluxes into the bottom and top of the vessel is seen with the vessel 0.8 m above the fuel. With the height of the vessel above the fuel reduced to 0.6 m the heat flux into the top face is still less than that into the bottom but both fluxes are within the range of heat fluxes in to the vessel sides. However, reducing the vessel height above the fuel to 0.4 m produces a significant reduction in the heat flux to the bottom of the vessel while that into the top face remains in the range of the heat fluxes into the vessel sides. It is therefore apparent that the vessel needs to be at least 0.6 m above the fuel surface in order to provide sufficient flame thickness for the heat flux into the bottom to be similar to that into the other faces. If the vessel height above the fuel exceeds 0.6 m, however, the heat flux into the top of the vessel can be expected to be somewhat less than that into the other faces.

THE EFFECT OF POOL SIZE

The average heat flux into each of the six faces of the Thick Slab Vessel, calculated from the vessel temperatures, for tests TSV-1, TSV-5 and TSV-6 are also shown in Figure 2. These three tests were identical except for the size of the pool of fuel which varied from 1 m beyond the vessel in each direction up to 3m. The heat fluxes into the sides of the vessel have again been joined by a line.

The heat fluxes in the tests with the pool extending 2.0 m and 3.0 m beyond the vessel are very similar, both in magnitude and uniformity. It is also interesting that both show the heat flux into the bottom face to be similar to that into the sides while that into the top is slightly below that into all the other faces. The heat fluxes in the test with the pool only extending 1 m beyond the vessel are very different to those in the other two tests, an extremely large variation in the flux into the sides being the most notable feature. Because of the small size of the fuel pool this test was very susceptible to wind and the flame cover was very non-uniform. Thus the heat flux into two of the sides and the top was very low while that into the other two sides and the bottom of the vessel was high, indeed higher than that measured into any of the faces in either of the two tests with the larger pools.

From the results of these tests it is concluded that, in order to provide a reasonably uniform heat flux around the vessel, the pool of fuel should extend at least 2.0 m beyond it on each side.

COMPARISON WITH RADIANT HEAT FLUXES

The heat fluxes discussed in the previous sections are those calculated from the temperatures of the steel slabs. Heat fluxes into each of the faces of the vessel have also been calculated based on the temperatures measured by the two DFTs on each face using the equation:

$$Q_T = \varepsilon\sigma(T_D^4 - T_S^4) + h(T_D - T_S) \tag{1}$$

where	Q_T	is the total heat flux
	ε	is the emissivity of the face of the vessel
	σ	is Stefan's constant
	T_D	is the temperature measured by the DFT
	T_S	is the temperature of the slab surface
and	h	is the convection coefficient

(note that all temperatures are in absolute units)

In this equation T_D has been used as an approximation to the flame temperature. The values assumed for the emissivity of the vessel surface and the convection coefficient were 0.9 and 10 $W/m^2{}^\circ C$ respectively, based on best available evidence (Burgess 1987). Because the convective component of the heat flux in a pool fire is dominated by the radiative component even a relatively large error in the assumed convection coefficient would only result in a small error in the calculated total heat flux.

The average calculated values of heat flux into each face in every test are shown in Figure 2 beside the heat fluxes determined from the vessel temperatures. The agreement between the heat fluxes calculated by the two different methods is fair but not good. The average magnitude of the error, over all the faces and tests, is 28%. In each test the heat fluxes calculated from the DFT temperatures show the same trends as regard relative magnitude of the heat fluxes into the different faces as do the heat fluxes calculated from the vessel temperatures but the magnitude of the variations between the faces is generally much greater. There is no evidence that the absorbed heat flux is restricted by the deposition of soot on the vessel surface.

Some typical calculated heat fluxes, as a function of time, are shown in Figure 1. It can be seen how the heat fluxes calculated from the DFT temperatures generally showed the same pattern of variation with time as those calculated from the vessel temperatures. However, the magnitude of the heat flux calculated from the DFT was often significantly different not only to that calculated from the vessel temperatures but also to that calculated from the other DFT. It is therefore concluded that the radiative heat flux can vary significantly even across a single face of the vessel and that this leads to the apparent disagreement with the heat flux calculated from the vessel temperatures.

The observed large local variations in heat flux is an important result since it demonstrates that, during the testing of an actual nuclear transport container, even if a number of DFTs were placed around it, the actual heat flux to which the container was subjected in the fire could not be accurately determined.

COMPARISON WITH THE IAEA REGULATIONS

There is currently significant debate as to how well the parameters specified in the IAEA Regulations represent the heat fluxes obtained in a practical pool fire test. As a contribution to this debate the heat fluxes measured in the Thick Slab Vessel tests have been compared against that obtained with the IAEA parameters.

If the surface of the Thick Slab Vessel is assumed to have an emissivity of 0.9 and the convection coefficient is assumed to be 10 $W/m^2{}^\circ C$, then the heat flux into a cold surface, using the IAEA parameters, will be given by:

$$Q = 0.9\times0.9\sigma\left((800+273)^4-(T_C+273)^4\right) + 10(800-T_C) \tag{2}$$

$$= 68.4 \text{ kW/m}^2$$

This heat flux is actually within 1% of the average flux measured in the tests and hence would appear to be, in general, a reasonable description of the average heat flux in a pool fire. However, as already noted, large variations in absorbed heat flux occur from test to test and from face to face and the maximum heat flux which can, locally, be obtained is far greater than this average value.

The IAEA regulations state that a surface absorptivity of 0.8 should be assumed if the actual value is not known, which it seldom is. Applying this value of absorptivity to the radiation heat flux reduces the total calculated heat flux to 61.7 kW/m^2 which is 9% below the average measured value. In the absence of a known value of surface absorptivity it would seem more appropriate to select a more pessimistic value, such as 1.0, especially since, in practice, the surface may have a fine layer of soot deposited upon it.

The average temperature measured by the DFTs on each of the faces of the Thick Slab Vessel, over all the tests, was 757°C which is in reasonable agreement with the flame temperature of 800°C specified in the IAEA regulations. However, it should be noted that the temperature measured by the DFT is related to the radiation flux rather than the thermodynamic temperature of the flames. If allowance is therefore made for the effective emissivity of the flames the IAEA regulations correspond to an effective black body temperature, as measured by a DFT given by:

$$T_{DFT} = \left(0.9(800+273)^4\right)^{\frac{1}{4}} - 273 \tag{3}$$

$$= 772°C$$

This is still above the average DFT temperature measured on the vessel surface in the tests but it should be remembered that significant variations in the measured temperatures were observed and both this temperature and the value of 800°C are well below the local maximum value recorded.

THE INFLUENCE OF THE VESSEL

The previous section examined the temperatures recorded by the DFTs at the vessel surface. A clearer picture of the 'flame' temperatures can be obtained by also looking at the temperatures measured by the DFTs in the rakes on each side of the vessel. On the upwind side of the vessel, where the flame cover was thin, the temperature measured by the DFT dropped off fairly quickly with distance from the vessel and the highest temperatures generally occurred at the vessel surface. However, on the downwind side of the vessel, where the flame cover was thick, the temperature measured by the DFTs initially increased with distance away from the vessel before decreasing near the edge of the flames.

It was considered probable that the low 'flame' temperature at the surface of the vessel was caused by the heat being absorbed by the vessel itself. The final test in the series, TSV-7, was therefore performed to confirm this by repeating an earlier test but with a thin-walled vessel. If the low temperatures were due to the heat adsorbed by the vessel then, since the vessel had only thin walls and hence a low thermal capacity, higher temperatures would be observed at the vessel surface. The average temperature measured by the DFTs in this test was 928°C. This is 69°C greater than the highest average temperature measured in any of the previous tests and 171°C higher than the average temperature over all the Thick Slab Vessel tests. It is therefore concluded that the Thick Slab Vessel, because of its high thermal capacity and consequently relatively low surface temperature, absorbs so much heat that it actually cools the fire. Similar behaviour was observed in tests at Sandia (Gregory et al. 1987) where the measured heat flux into a large calorimeter was less than that into a small calorimeter.

DISCUSSION

From the results of the seven Thick Slab Vessel pool fire tests it is apparent that improvements could be made to the practical specification in the IAEA regulations for performing a pool fire test. The suggested changes are:

1. The specified height of the vessel above the fuel should be changed from "1.0 m" to "between 0.6 m and 1.0 m" since lowering the height of the vessel to 0.6 m above the fuel does not significantly affect the heat fluxes into the vessel but could improve the flame uniformity, especially for large containers.

2. The specified minimum size of the pool of fuel should be changed from "at least 1 m beyond any external surface of the specimen" to "at least 2 m beyond any external surface of the specimen" since the flame cover with a pool of the current minimum size was shown to be very poor whereas very little difference was discernable in the heat fluxes with pools extending 2.0 m and 3.0 m beyond the vessel.

Nuclear transport containers can be generally divided into two categories as regard their resistance to a pool fire. The first category contains material of low activity which generates negligible heat and is protected against the pool fire test by an insulating material on its exterior. This type of container will absorb negligible heat from the fire and the surface could reach temperatures as high as 1100°C, as measured in the test upon the thin-walled vessel and in tests on a small shock absorber (Fry 1990). The second class of container contains highly active material and survives the pool fire test by merit of its large mass and high thermal capacity. This type of container will absorb significant heat from the fire which will cool the flames local to the container so that the flame temperatures near the vessel may be below 800°C, as measured in the Thick Slab Vessel tests.

For modelling purposes it would be useful to have a single set of boundary conditions which would represent, in a simple manner, both these situations with reasonable accuracy and it is believed that a surface heat flux calculated using the following equation satisfies this requirement:

$$Q = 0.3\varepsilon_S\sigma\left((1100+273)^4-(T_S+273)^4\right) + h(1100-T_S) \tag{4}$$

where ε_s is the emissivity of the container surface
σ is Stefan's constant
T_s is the temperature of the surface (°C)
and h is the convection coefficient

This equation represents a flame temperature of 1100°C, so containers with insulating material at their surface will experience surface temperatures close to this value, as desired. However, the heat flux into the cold surface of a massive body obtained from this equation is in good agreement with that measured in the thick slab vessel tests and also that obtained from the parameters specified in the current IAEA regulations. The factor of 0.3 in front of the radiative term in the equation is responsible for ensuring this level of heat flux to massive, cold bodies. This factor is equivalent to a flame emissivity but physically represents not a reduced emissivity but a reduced effective flame temperature adjacent to the surface of the container.

The above equation for produces a heat flux into a cold body which is 5% lower than that obtained from the current IAEA regulations. However, for containers with insulating surfaces the increase of 300°C in assumed flame temperature may result in increases in internal temperatures typically 40% higher than obtained with the current IAEA parameters. It should be noted that the above equation for surface heat flux is intended to represent that obtained in a practical pool fire test upon a relatively large container with an unfinned surface. The applicability of this equation to heat fluxes in pool fire tests on containers with finned surfaces has not been considered.

CONCLUSIONS

A series of seven pool fire tests have been carried out on a large, cubic container to measure temperatures and heat fluxes and determine how the magnitude and uniformity of these are affected by the height of the container above the fuel and the size of the fuel pool.

The average heat flux into the faces of the Thick Slab Vessel was 68 kW/m^2. However, significant variations in absorbed heat flux occurred from face to face and with time. The agreement between the heat fluxes calculated from the vessel temperatures and from the DFTs on the vessel surface was only fair and it was concluded that the discrepancy was caused by significant variations in the local heat flux across even a single face of the vessel.

The effect of the height of the vessel above the fuel upon the magnitude and uniformity of the absorbed heat flux was not significant but, below 0.6 m, the heat flux into the bottom face of the vessel was significantly reduced. No significant difference in absorbed heat flux was observed as the size of the pool of fuel was increased from 2 to 3 m beyond the sides of the vessel in each direction but with the pool only extending 1 m beyond the vessel the flame uniformity was significantly reduced.

The average temperature measured by the Directional Flame Thermometers on the surface of the vessel, over all the tests with the Thick Slab Vessel, was 757°C. Significantly higher temperatures were recorded in the flames away from the vessel and it was concluded that the reduction in effective flame temperature close to the vessel was due to the heat being absorbed by the vessel itself. When the vessel had only a low thermal capacity significantly higher temperatures were recorded.

It was concluded that improvements could be made to the prescription of a practical pool fire test in the IAEA regulations. Recommendations have been made for changing the specified height of the container above the fuel and the size of the pool of fuel. Boundary conditions have been presented which represent, with reasonable accuracy, the measured heat fluxes in a pool fire test into both massive, cold, unfinned surfaces and into low thermal capacity or insulated surfaces.

REFERENCES

BLACKWELL, B. F., DOUGLAS, R. W. and WOLFE, H. 'A User's Manual for the Sandia One-Dimensional Direct and Inverse Thermal (SODDIT) Code', Sandia Report SAND 85-2478, 1987

BURGESS, M. H. 'Heat Transfer Boundary Conditions in Pool Fires', in: Packaging and Transportation of Radioactive Materials (PATRAM '86), STDI/PUB/718 (Vienna: IAEA), 1987

BURGESS, M. H. & FRY, C. J. 'Fire Testing for Package Approval', International Journal of Radioactive Materials Transport, Vol 1 No 1 pp 7-16, 1990

FRY, C. J. 'Pool Fire Testing at AEE Winfrith', in: Packaging and Transportation of Radioactive Materials (PATRAM '89), CONF-890631 Vol 3, pp 1587-1594, 1989

FRY, C. J. 'Pool Fire upon a Balsa-Filled Shock Absorber', UKAEA AEE Winfrith report, AEEW-R2475, 1990

GREGORY, J. J., MALTA R. & KELTNER N.R. 'Thermal Measurements in a Series of Large Pool Fires', SAND85-0196, Sandia National Laboratories, Albuquerque, 1987

'IAEA Regulations for the Safe Transport of Radioactive Material', 1985 Edition, STI/PUB/691, Safety Series No 6 (Vienna: IAEA), 1985

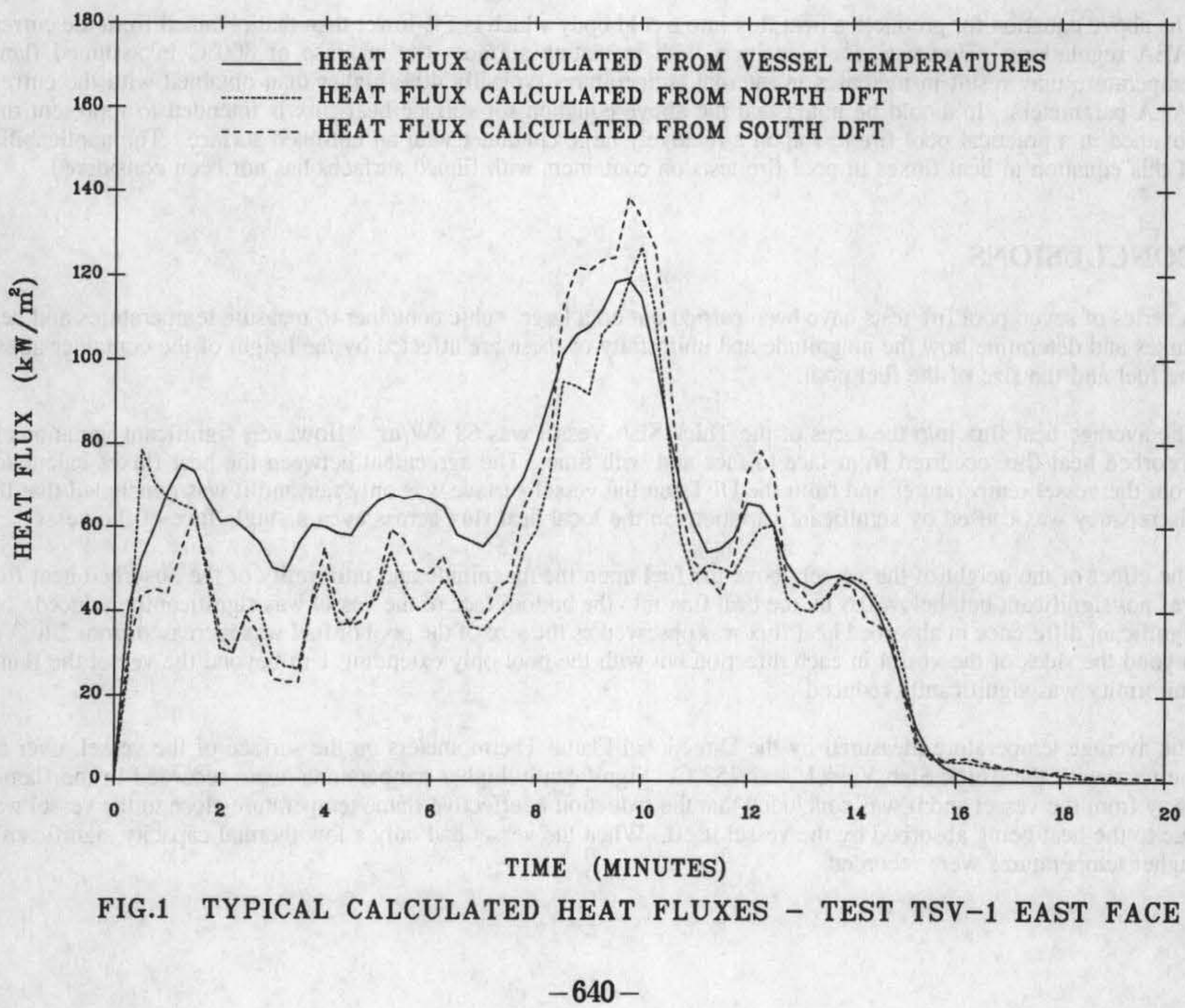

FIG.1 TYPICAL CALCULATED HEAT FLUXES - TEST TSV-1 EAST FACE

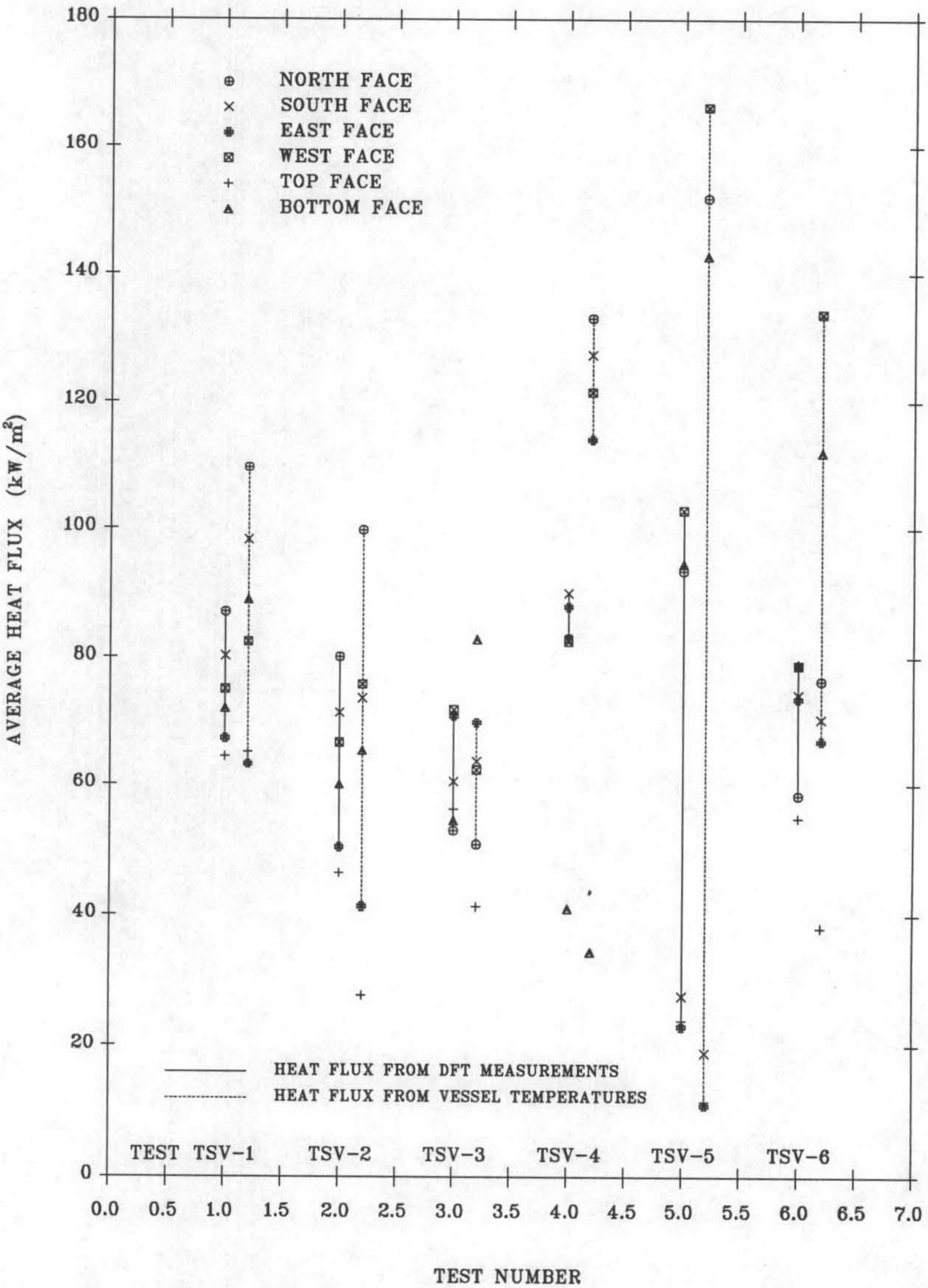

FIG.2 CALCULATED AVERAGE HEAT FLUXES

Session 22:

REGULATIONS-II

Chairman : R. E. Luna
Co-Chairman : S. Kikuchi
Coordinator : T. Itoh