SUPPLY AND DEMAND SIDE BENEFITS AND COSTS OF LOW COST URBAN ELECTRIFICATION IN MALAWI: A CASE OF MBAYANI TOWNSHIP

MARGARET NJIRAMBO MATINGA

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University of Cape Town

DECLARATION

I, Margaret Njirambo Matinga declare that this dissertation is my own original work. It is being submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering (Energy studies) at the University of Cape Town. It has not been submitted before for any degree or examination at any other university.

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MARGARET NJIRAMBO MATINGA

Dated at _____ this day of _____ 2004

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This work is dedicated to my mother and my friends, for believing in my abilities and for their unwavering moral support.

ABSTRACT

This study investigates the supply and demand side benefits and costs of low cost urban electrification in Mbayani Township in Blantyre City in Malawi. The low cost urban electrification program, which used compact ready boards to provide electricity to poor households in Mbayani, is the first such program in the country. The study therefore examines the strategies used to assess how they impact the service provider and the newly electrified households in terms of benefits and costs in order to draw lesson for similar programs in the future.

Using an interview, the study first examines the financing and planning strategies, technologies used, tariff design and cost recovery strategies on the supply side. On users' side, the study uses a sample household survey to examine the effects of electrification on households' expenditures, fuel use and on the small and medium scale enterprises sector in Mbayani. The study conducted key informant interviews to assess community leaders' perception of the program. In addition, the study reviews the South African electrification program from which it draws lessons for Malawi.

On the supply side, the strategies used reduced electrification costs and enabled the service provider to use infrastructure that was previously under-utilised. However, limited financing and planning which ignored user needs has negative implications on the program outcomes. Electricity tariffs were based on a monthly flat rate tariff, which is likely to negatively impact on the utility's revenue. However, at the scale that the program was carried out, this impact is negligible. The tariff nevertheless ensures cost recovery over a period of 5 years. While lack of data from the utility hindered detailed analysis of the supply side impacts, the study concluded that the strategies used yielded net costs for the utility.

On the demand side, the study found that electrification strategies used had a positive impact on households' energy burden and budget control and that most households have switched to electricity for lighting, powering radios and partly for cooking. Major barriers in maximising benefits are high costs of electrical appliances and poor supply quality.

The study recommends that future programs should use holistic participatory planning and should diversify sources of funding. Electrification strategies must also target small and medium enterprises and promote support for acquisition of better quality appliances.

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1.1 Geography and demography of Malawi

Malawi is a Southern African country situated between latitudes 9°10′ and 17°7′ South and longitudes 32°41′ and 35°56′East and is bordered by Tanzania, Zambia and Mozambique (Figure 1). The country has a total area of 118 484 square kilometres, of which 20% is covered by water bodies, including Lake Malawi. According to the National Statistics Office (NSO), the population in the country grew at an average of 1.9% per annum between 1987 and 1998 and stood at 9.93 million inhabitants in 1998. The Population and Household Census further estimated that the national population density in Malawi stood at 105 persons per square kilometre of land in 1998 and that up to 49% of the Malawi population comprises of males while 51% are females (NSO, 2000a: 7). Meanwhile females head 24% of Malawian households. Up to 86% of the Malawi population live in rural areas.

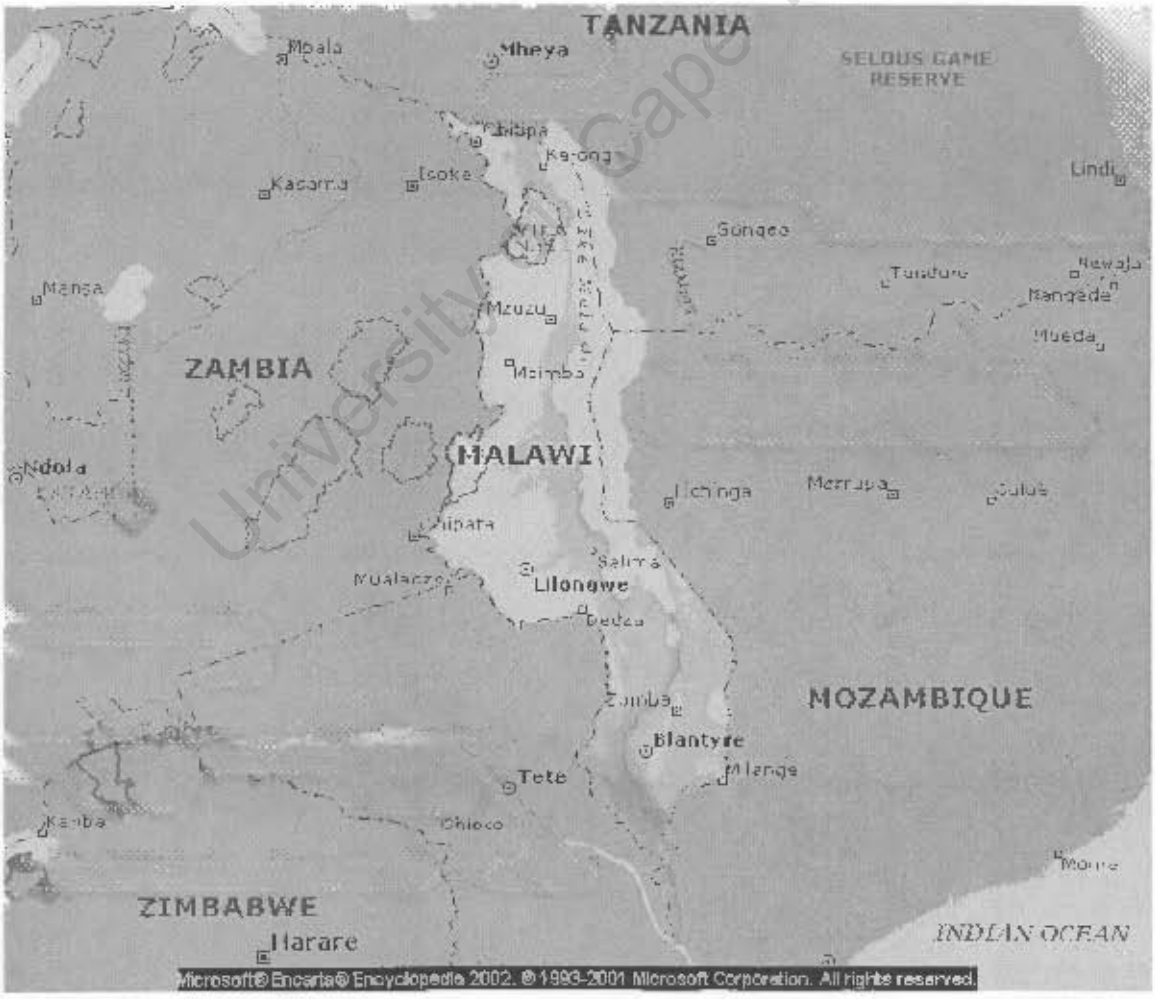


Figure 1: Map of Malawi

LIST OF ACRONYMNS AND ABBREVIATIONS

AC	Alternating current
AFREPREN	African Energy Policy Research Network
CRB	Compact ready boards
DC	Direct current
DME	Department of Minerals and Energy
DOE	Department of Energy
EDRC	Energy Development and Research Centre
ESCOM	Electricity Supply Commission of Malawi
Eskom	Electricity Supply Commission (the South African power utility)
GDP	Gross Domestic Product
GW	Giga Watt
GWh	Giga Watt-hour
JICA	Japanese International Cooperation Agency
Kg	Kilograms
kW	Kilowatt
kWh	Kilowatt-hour
LPG	Liquefied Petroleum Gas
MK	Malawi Kwacha
MW	Megawatt
PVC	Poly Vinyl Chloride
SADC	Southern Africa Development Community
SARPN	Southern African Research on Poverty Network
SME(s)	Small and Medium Enterprise(s)
US$	United States Dollar

1.2 Economic development and poverty in Malawi

The Malawi economy is dependent on agriculture, most of which is subsistence farming. A total of 2.2 million families out of 2.9 million families in Malawi, representing 76% of Malawian households are involved in subsistence farming on about 1.8 million hectares of land (NSO, 1998). A total of 60.4% of all exports are tobacco exports, while tea exports and sugar exports contribute 9.1% and 9.0% respectively to Malawi's exports earnings (NEC, 2002:14). Agriculture constitutes 40.3% of the GDP, (NEC, 2002:14-16) and agricultural products comprise 80% of all exports. Agricultural activities provide 45% of formal employment (NSO, 1998), closely followed by small and medium scale enterprises (SMEs), which employ 38.5% of the country's labour force. The SME sector contributes 15.6% of Malawi's GDP (NSO, 2000b:8).

In 2001, Malawi's average GDP declined by 1.5% per annum (NEC, 2002:6), compared to an average GDP growth of 1.95% per annum in the Southern African Development Community (SADC) (Madakufamba, 2003:6). GDP per Capita in Malawi stood at an estimated US$ 141 (SADC, 2003), qualifying Malawi as one of the least developed countries. In terms of the Human Development Index[1] (HDI) ranking, the country ranked 163 out of 175 countries in 1998 (UNDP, 2002).

Malawi social indicators further highlight the poor socio-economic status of the country. Infant mortality in 1998 was at 137 per 1000 live births, which was higher than the SADC average of 107 per 1000 live births (SARPN, 2003). Under-five mortality stood at 124 per 1000 births (NSO, 1998). Life expectancy in 1998 among men in Malawi stood at 37 years and at 43 years among women, with an overall average national life expectancy of 39 years (NSO, 1998) compared to the average life expectancy of 49 years in SADC in 1998 (Malaba, 2001:28)

Up to 76% of employed persons in Malawi are employed in subsistence farming (NSO, 1998) and hence their earnings are low, seasonal and susceptible to weather patterns and natural disasters.

1.3 The Malawi energy sector

At national level, about 94% Malawian households depend on biomass for their energy needs (NSO, 1998) and only about 6% of the population has access to electricity (Potani, 2002. Pers. Comm.). According to Semu and Mawaya (1999:12), the Malawi household sector uses three

[1] An index used the to measure overall developmental achievements based on longevity as measured by life expectancy at birth, education attainment measured by combined adult literacy and gross enrolment ratio and standard of living as measured by GDP per capita by purchasing power parity.

times as much biomass fuel as the agricultural sector and twelve times as much as the industrial sector.

Hydro-power is the dominant source of electricity, providing over 90% of the country's electricity production. Other potential sources of electricity include coal, solar and bagasse, but these are under-utilised due to poor planning, limited financing and lack of technical expertise among other factors (Matinga, 2003).

The household sector consumes the smallest amount of commercial fuels, accounting for 8% of the commercial fuels share, while the transport sector accounts for the largest share, at 42%. The agricultural sector consumes 12% whilst the industrial sector consumes 19% of all commercial fuels in Malawi (GoM, 2001a:13).

The final energy balance in Malawi is such that firewood and charcoal comprises 93% of the energy balance, while petroleum products comprises 3.5% (GoM, 2001a:12) of the energy balance. Electricity, coal and agricultural residues contribute 2.3%, 1% and 0.2% respectively.

Concerns over the over-dependence on traditional biomass contributed to the development of the first ever, comprehensive energy policy in Malawi and power sector reforms in 1998. The overall goal of the Malawi energy policy is to 'promote Malawi's socio-economic development and contribute to poverty reduction, through sustainable provision of equitable, efficient and affordable energy services' (GoM, 2001a:17).

Power sector reforms were instituted in an effort to improve the performance of the electricity sector which faced problems that include slow progress in electrification, capital constraints, poor technical and financial performance (including revenue collection and tariff setting) and low human capital efficiency (Chiwaya, 1999, Matinga, 2003).

An assessment of the legal and regulatory framework and the progress of the power sector reforms however showed that little attention is paid to the energy needs and electrification of the urban poor (Matinga, 2003). In practice, only one pilot program has attempted to address access to electricity among the urban poor and one other program uses prepayment meters to improve affordability of electricity and revenue collection among middle-income urban residents. Both these programs have been carried out on a small scale.

1.4 Urbanisation, poverty and energy in Malawi

1.4.1 Urbanisation and poverty in Malawi

Although Malawi is primarily rural, with 86% of its population living in rural areas (NSO, 1998), the urban population is increasing due to both local population growth and rural-urban migration (Figure 2). This trend is likely to continue in the long term and the Malawi State of

the Environment Report, estimates that in 2018, the urban population will have increased by 366% from 1988 level when less that 1 million people lived in urban areas (GoM, 2001b:23).

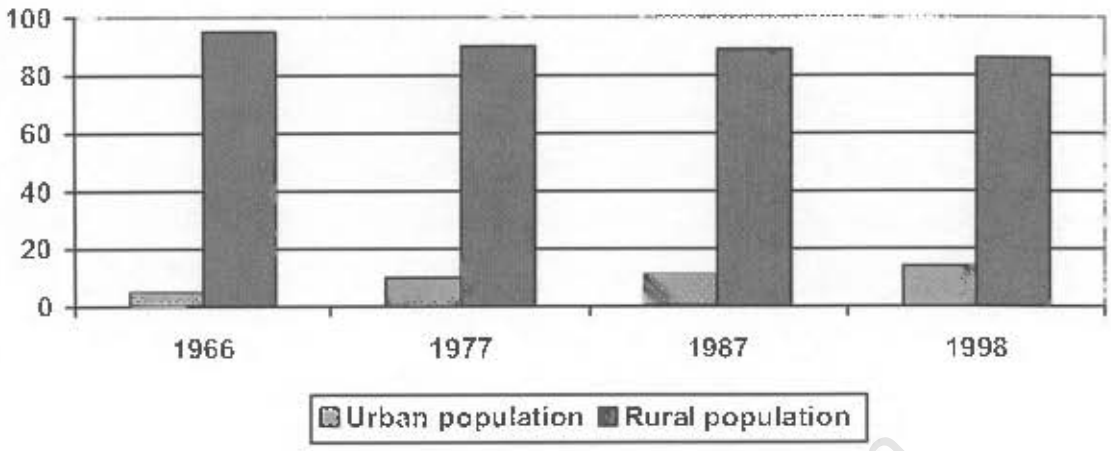


Figure 2: Urban and rural population growth trends in Malawi (1966-1998)
Source: Adapted from NSO, 1998

In addition to the increasing population in urban areas, the population growth in urban areas is higher, at 6.7% per annum between 1987 and 1998, compared to the national population growth of 1.9% between the same period (NSO, 1998). Urban population growth rate in Malawi in 1998 was also higher than the average urban growth rate in Sub-Saharan Africa of 5.2% per annum in 1999 (Karekezi and Majoro, 2002:1015).

The urbanisation trend in Malawi is exerting pressure on existing infrastructure and increasing the demand for public goods and services such as energy services, water, sanitation, and health facilities. In 1977, 44% of the population in Blantyre, Malawi's commercial city district, lived in unplanned squatters and Traditional Housing Areas (THAs) and by 1999 this percentage had increased to 55% of the population in Blantyre (GoM, 2001b: 13). In 2000, 70% of the urban population lived in THAs, signifying increasing infrastructure needs. Population density has also increased in the main urban centres of Blantyre, Lilongwe, Mzuzu Cities and Zomba (Table 1), where the population density has nearly doubled from the 1977 levels (GoM, 2001b:22).

Year	1997	1987	1998
Lilongwe	114	159	219
Blantyre	203	293	402
Mzuzu	29	42	59
Zomba	137	171	212

Table 1: Population density in main urban centres in Malawi in persons per square km
Source: GoM, 2001

The Integrated Household Survey conducted by the NSO in 1998 showed that up to 55% of the population in urban areas in Malawi live below the national poverty line (NSO, 1998). There is

also increasing poverty in Malawi urban areas, as illustrated by the fact that in 1994/95, 75% of all urban households had incomes of less than US$ 133 per household per month (GoM, 2001a:14) while over half of these had incomes of less than US$ 76 per household per month and 26% earned less than US$ 33 per household per month. In contrast, an analysis of 1998 the Integrated Household Survey data shows that up to 75.4% of urban households had monthly incomes of less than MK1000 per household per month (NSO, 2000a:13) which in 1998 was equivalent to US$ 14 or US$ 67 in 1995 terms. Inflation is also often higher in urban areas and was at 43.3% in 2000 while in rural areas, inflation was at 29.2% in 2000 (GoM, 2001b:14).

Urban unemployment in 1998 was estimated to be 46.5% (NSO, 1998) Meanwhile the national GDP contribution of the manufacturing sector, which is a significant employer in urban areas, decreased by 14.2% in 2001 after another decrease of 3% in 2000 (NEC, 2002:6). One reason for this is the closing down of a number of companies, resulting in substantial loss of employment especially for poor urban dwellers who supply labour to the manufacturing industry.

The HIV/AIDS pandemic has also contributed to rising poverty with an increase in single parent households, child-headed households and increases in number of household members depending on decreasing resources per capita as wage earners may be unable to work due to sickness or death and as families take in AIDS orphans. In 2001, UNICEF estimated that Malawi had 470,000 AIDS orphans between the ages of 0 and 14 (UNICEF, 2003).

1.4.2 Energy use and poverty links in urban areas in Malawi

Only 30% of the urban population had access to electricity in 1998. Up to 68.2% depended on paraffin for lighting and for cooking, 69% of the urban population depended on firewood whilst 15.5% of the urban population depended on charcoal for cooking (Table 2).

Source	Firewood	Charcoal	Electricity	Paraffin	Candles	Gas	Grass	None
Lighting	1.0	0	27.5	68.2	2.6	0.1	0.5	0.2
Cooking	69.0	15.5	13.3	1.8	0	0.1	0.1	0.2

Table 2: Fuel used for lighting and cooking in urban Areas in Malawi
Source: Adapted from NSO, 1998

The wood and charcoal consumption per capita for urban households in Malawi was estimated at 1,120kg equivalent of wood per annum compared to 680kg equivalent of wood per annum for rural households (GoM, 2001b:165). This means that urban households consume an average of 1.65 times more wood than their rural counterparts per capita per year.

The higher equivalent wood usage per capita in urban areas implies that in terms of energy use, urban populations contribute more per capita, to firewood related deforestation than rural

populations and may be more at risk of adverse effects of indoor air pollution per capita (assuming equal type of fuel, similar ventilation and length of cooking times).

A number of studies have also linked use of traditional biomass to acute respiratory infections (ARIs) due to poor indoor air quality (Bergstra, 1988, Wallmo and Jacobson, 1998). It is interesting to note that incidences of ARIs in urban areas in Malawi are at least 1.8 times more common than in rural areas (NSO, 1998). Although several factors including opportunistic infections from HIV/AIDS and urban pollution contribute to this, use of firewood and charcoal would exacerbate the situation.

Overdependence on traditional biomass is also expensive in that traditional biomass has lower end use efficiencies of 10% and 35% for firewood and charcoal respectively compared to 75% to 85% for electricity (Alberts et al, 1997:34). The cost per unit of useful energy of commonly used fuels in poor households is also higher than cost per useful unit of electricity. Studies conducted by the Department for International Development (DFID) in Uganda (DFID, 2002:7), estimated that light generated from a paraffin lamp costs 70 times more than the equivalent light from mains electricity, while light from a candle costs 150 times more and power from a battery costs 10 to 30 times more than power from mains electricity. In addition, in practice, poor households use one candle or one paraffin lamp as an equivalent of one electric bulb (and sometimes as an equivalent to two bulbs if rooms are adjoined). This means that the fact that paraffin lamps and candles provide poor quality light is exacerbated, which may deter study among school going children.

1.4.3 Energy, poverty and SMEs in urban areas

In 1992, the NSO carried out a study of the small and medium enterprises (SME) sector known as the Gemini Study and a follow up study was carried out in 2000. The NSO defined SMEs as enterprises that employ between 1 and 50 persons and this employment may include the owner, have no multiple branches and sell at least 50% of their goods and services (NSO, 2000b:3). Within the definition of SMEs is the sub-grouping of enterprises, classified as micro-enterprises which according to the NSO definition, comprises of those enterprises that employ between 1 and 4 persons including the owner. Although 80% of all SMEs are based in rural areas where 86% of Malawi's population reside, there has been an increase in SMEs in urban areas. SMEs are mostly prevalent in low income households (Table 3) as a strategy to diversify income sources and alleviate poverty (NSO, 2000b:11).

Income Group	Percentage Composition
High income households	3.1
Low income households	12.4
Community	1.0
Industrial	0.1

Table 3: Occurrence of SMEs among income groups in urban areas in Malawi
Source: NSO, 2000b

In urban areas, SMEs provide employment to at least 23% of the urban labour force (NSO, 2000b:65). In terms of gender, females own about 34% of SMEs in Malawi and females contribute up to 42% of the labour in SMEs. There is also active contribution by women in spouse-owned SMEs. Micro-enterprises dominate the SME sector in Malawi and constitute 90% of all SMEs in the country (Table 4).

No of Employees	Percentage of Total
1	44
2	30
3	10
4	6
Total	90

Table 4: Composition of micro- enterprises in Malawi
Source: NSO, 2000b

The Gemini Survey estimated that up 47% of low income urban households derive all of their incomes from SMEs (NSO, 2000b: 63) and up to 73.3% of all SMEs are conducted near or in the home. This means in most cases, households use household energy supplies to meet the energy needs of the enterprise.

The versatility of electricity also enhances productivity since it can be used for a wider range of productive uses such as mechanised food processing, cooling drinks or preserving food which can be sold, leading to the development of small and medium scale enterprises (SME).

1.4.4 Urbanisation and the electrification paradox

While urbanisation exerts pressure on available resources for public services providers, in the electricity sector, it also provides some unique opportunities. The urban poor often settle in the peripheries of city centres, central business districts and low density non-poor suburban areas where there is access to electricity. As a result, they are close to electricity infrastructure, which makes extension of the electricity networks to poor urban households cheaper in comparison to rural areas. In most cases, this infrastructure is under-utilised because the urban poor are unable to pay for connection costs and no special interventions have been instituted to assist them to gain access to electricity. In addition, land-access problems force poor urban households to

build their homes close together, making electrification costs lower because of shorter grid connection distances from one house to another.

The emergence of new pro-poor technologies such as compact ready boards which reduce the need for wiring and its related costs and pre-payment meters has also been beneficial in that it has reduced some of the barriers that hindered poor households from gaining access to electricity. For the utility, the removal of these barriers means that previously under-utilised infrastructure can now be used and the utility can gain revenue from it. This is further aided by the likelihood of poor urban residents to accept new technologies compared to rural residents (Howorth, 1997:16).

Diverse sources of incomes among the urban poor also make it likely for them to pay for services, especially because the urban poor are used to paying for fuels while the rural population often obtain traditional fuel "free of charge" because they fetch it themselves.

Further more, the urban poor often engage in SMEs to enhance their income base. The fact that urban SMEs have better access to markets often makes urban SMEs more profitable than rural SMEs making them an attractive customer category for the utility. Electrification of SMEs has the added benefit, to the utility, of ensuring that the system load on the network is not purely domestic. This is good for generation design as it reduces the need for peaking capacity which is expensive and ensures optimum network utilisation (Fakira, 1994:16).

1.5 Objectives of the study

ESCOM has implemented a pilot program to increase access to electricity among the urban poor by using compact ready boards to reduce connection cost. While using special pro-poor strategies to electrify is a positive development, there is need to ensure that such programs are well planned and do not have a negative impact on the financial viability of the utility. In addition, their implementation should not exacerbate poverty among the target community. The study is therefore carried out with the following objectives;

1. To investigate how the low cost electrification program in Mbayani was planned and financed as well as the supply and technological options used.
2. To investigate whether and how the costs of electrification are recovered and examine the effect of the tariff design on the utility's revenue intake.
3. To assess the effect that the introduction of electricity in the newly electrified households has on their energy burden, energy budget control and fuel choices as well as trends in electrical appliance acquisition.
4. To assess whether the introduction of electricity in the program area has had a positive impact on the small and medium enterprises (SME) sector in the area
5. To examine the perceptions of users on the advantages and disadvantages of low cost electricity.
6. To review the South African electrification process and learn lessons from its experiences.

1.6 Chapter outline and scope

The first chapter introduces Malawi and provides background information on its demography, economic development and poverty. It also briefly discusses the Malawi energy sector, urbanisation trends, poverty and SME development in Malawi and their linkages to energy services, and in particular, electricity. It then summarises the objectives of the study.

The second chapter explains the problem statement and research design and methodology. It presents two hypotheses to be tested by the study, including the methodologies and indicators used to test each hypothesis. It also presents a description of the study area, the sampling and data collection methods and the challenges of the study. Finally, chapter two discusses possible sources of errors in data collection and analysis and ways of dealing with these to minimise errors.

Chapter three discusses study findings. Chapter four reviews electrification strategies used in South Africa and draws lessons from these experiences for Malawi. Chapter five provides conclusions and policy recommendations of the study, including brief discussions on challenges presented by particular recommendations and how to deal with these challenges.

CHAPTER 2: PROBLEM STATEMENT, RESEARCH HYPOTHESIS AND METHODOLOGY

2. Introduction

This chapter clarifies the research problem and explains the research questions and study methodologies, designed to give direction to the study. Two hypotheses were formulated in relation to the perceived problem and these form the basis of the thesis. The chapter presents study indicators used to test the hypotheses, challenges of the study and possible sources of errors in analysis.

2.1 Statement of the problem

Compact ready boards were used to electrify poor urban households in Mbayani Township in Blantyre city in Malawi. However, no follow up studies have been carried out to assess costs and benefits of the program. Meanwhile, high poverty levels among the urban poor hinder households from obtaining access to electricity. This calls for need for the electricity service providers to use innovative, pro-poor technologies to reduce the costs of electrification. The challenge in coming up with such strategies is in ensuring that these pro-poor electrification strategies do not negatively impact on the financial performance of the electricity service providers. On the other hand, the strategies should also result in net benefits to the electricity users. For example, conventional electrification strategies used in the past did not take into account factors such as income levels and cash flow patterns. All consumers were therefore billed based on a 30-days pay cycle that mimics pay patterns of salaried employees despite the fact that most Malawians, in particular the poor are not in formal employment and may therefore not have monthly incomes that are based on the 30-days pay cycle. In addition, standard reticulation and wiring are used despite the low demand of low-income consumers and the fact that the poor often live in semi-permanent houses that cannot meet the wiring standards required by electricity supply regulations. As a result, electricity has been very expensive for most urban poor households. Use of compact ready boards and the special tariff design used in Mbayani therefore presents unique opportunities for dealing with some of the challenges of electrifying poor urban households.

However, the real impacts of the low cost electrification program in Mbayani, on both the supply side and the demand side remain unknown because the program continues to exist without the benefit of monitoring studies. Continuing or discontinuing such a program can therefore not be justified, hence the need for benefits and costs study.

2.2 Research questions, objectives and study hypotheses.

2.2.1 The Research questions and study hypothesis.

The aim of the study is to analyse the benefits and costs (constraints and disadvantages) of using compact ready boards to electrify poor households in Mbayani, an urban township in Malawi and to assess the benefits and costs of the tariff design used. The results of the study are to form an information base from which lessons for future pro-poor urban electrification projects and policies in Malawi can be drawn. The research question that the study intends to address is;

> What are the benefits and costs, on both the supply and demand side, of electrifying poor households using compact ready boards and the tariffs used in Mbayani Township in Blantyre city in Malawi?

The research aims at assessing whether or not the strategies used in the Mbayani low cost electrification program should be adopted for large scale and future urban electrification programs based on the financial implications on the utility and on the socio-economic impacts of the program design on targeted households. On the demand side, the study intends to assess implications of the strategies used, including terms of payment and tariff design on households' energy burden, fuel choices, the impact on the SME sector in Mbayani and users' perceptions.

A literature review on benefits and costs of electrification (Lötter and Mullins, 1995) showed that electrification benefits and costs can be categorised into three broad categories as below;

1. Benefits and costs of micro-economic significance at household level, which can include decreased spending or increased spending on energy sources due to energy resource diversification or fuel substitution. These benefits and costs can be quantified and priced.
2. Benefits and costs that can be quantified but not [easily] priced such as time saving and clean indoor air and other health related impacts.
3. Benefits and costs that cannot be quantified and priced such as changes in perceptions among beneficiaries of electrification programs. Examples of such benefits may include improved sense of security due to security lights installed around houses and increased sense of social inclusion in the development mainstream, whilst examples of costs would be loss of customer goodwill and loss of morale due to unreliable electricity supply.

In line with these categories and the research question, two hypotheses were developed from which a number of research questions were formulated to clarify the hypotheses and give scope and direction to the research. In order to direct the testing of the hypotheses, indicators were formulated. The next section outlines the selected hypotheses, their related research questions, methodology and indicators.

2.3 Hypothesis 1: The design of the low-cost electrification program in Mbayani results in net benefits for the power utility (ESCOM)

The related questions for the first hypothesis are as follows:

- How were financing and planning for the Mbayani low cost electrification program carried out?
- What supply and technology options were considered and how were they selected?
- Are the costs of electrification and energy use in Mbayani recovered by the utility?
- How are the costs of electrification and energy use recovered?
- What has been the effect of the tariff design used in Mbayani on ESCOM's revenue take in?

2.3.1 Methodology

The first study hypothesis was tested mainly through the review of literature and an interview of a suitable utility employee. Although 10 utility personnel were initially targeted for interviews, due to availability constraints, only one suitable employee, who is the utility's Marketing Manager and coordinator of the Mbayani low cost electrification program, was eventually interviewed.

2.3.2 Indicators

- Cost of compact ready boards.
- Cost per connection in low cost electrification program compared to connection costs in conventional electrification programs.
- Method of cost recovery.
- Percentage of cost recovered since onset of program.
- Contribution of revenue from new users to total revenue.
- Losses or profits from new users as percentage of loss or profit for all domestic users.
- Difference between tariffs used in conventional electrification and tariffs used in Mbayani.

2.4 Hypothesis 2: The program design of the low cost electrification program in Mbayani yields net benefits for the electrified households

The research questions related to hypothesis 2 are as below:

- What tariffs are being paid under the Mbayani low cost electrification program?
- How has the introduction of electricity in the newly electrified households in Mbayani affected the energy burden of these households?
- How are terms of payment of electricity affecting the households' control of their energy budget?
- How has electrification and its related tariff design affected the fuel choices of the newly electrified households in Mbayani?
- What are the trends for electrical appliances acquisition?
- What contributions has the low cost electrification program made to the SME sector in Mbayani?
- What are the benefits and costs of the compact board electricity as perceived by the consumers in Mbayani?

2.4.1 Methodology

The second study hypothesis was tested using a household survey carried out in a section of Mbayani Township in Blantyre city, where compact ready boards were used to electrify poor households. Mbayani is one of the high density, high poverty townships in Malawi and was selected by the power utility ESCOM as a beneficiary of the low cost electrification program in which compact boards were used. Currently, Mbayani is the first and only area in Malawi where compact ready boards have been used by the utility and was therefore the only place where the second hypothesis could be tested. Apart from the household survey, two key informant interviews were carried out with community leaders with the aim of assessing the perceptions of the community leaders.

2.4.2 Indicators

- Tariffs structure imposed by utility on compact ready board electricity consumers.
- Energy burden of newly electrified households before and after electrification.
- Terms, including frequency and amounts of electricity payments.
- Fuels used by newly electrified households before and after electrification.
- Electrical appliances ownership trends in households after electrification.
- Contributions made by electricity to SME activities.
- Number of SMEs started as a direct result of electrification.
- Advantages and disadvantages of compact board electricity as perceived and ranked by consumers in order of perceived impact.

In addition to surveys done in Malawi, a literature review of the electrification process in South Africa was carried out to draw lessons which can be adapted in Malawi's future electrification programs.

Due to the low levels of electrification in Sub-Sahara African countries, a number of countries in Africa have undertaken low cost electrification initiatives to improve access to electricity in their countries. Although there are variations in the electrification program designs due to factors such as economic status of countries, research and technical expertise and financial status of implementing agencies, the key aspects of the low cost electrification programs are the same and include unique financing and planning mechanisms, tariff designs and use of pro-poor technological options.

Countries that have implemented low cost urban electrification programs in SADC region include South Africa, Zambia, and Mozambique. In South Africa, a number of options including compact ready boards and load limited supplies are some of the many options that have been tried. In Zambia, the *Pamodzi* electrification program targets poor urban households and included provision of electrical appliance to promote electricity use in newly electrified

poor urban households (Mehlwana, 1999:28), while in Mozambique, compact ready boards were used to reduce wiring costs for poor urban households. Although Zambia and Mozambique are more similar to Malawi in terms of limited technical expertise and options, level of economic development and performance of the implementing utilities, the case of South Africa was selected because of the wide range of options that have been used and because of the availability of pre-electrification and post-electrification research data on which to base a literature review. In addition, the case of South Africa registered a relatively higher level of success and therefore provides an interesting case for learning how to implement successful electrification program.

2.5 The study area, sampling and data collection

2.5.1 Description of study area

Mbayani is an unplanned township, in Blantyre city, which is Malawi's second largest city and also the country's commercial city. The township is situated immediately (about a kilometre) north of Blantyre City centre and central business district. It has a population of 43,000 inhabitants (AFRICON, 1999:171), which based on the average number of households in Malawi in 1998, means that the township has about 10, 000 households. The township has characteristics found in most poor unplanned urban areas, which include high differentials in incomes, crowded and unplanned housing and poor sanitary conditions. Most of the households supplement their low incomes by engaging in small scale, usually home-based businesses. Informal business activities in Mbayani contribute 7% of all informal activities in Blantyre, which is high considering that Mbayani comprises 8% of population in Blantyre (AFRICON, 1999:171).

Common income generating activities in Mbayani include road side sales of snacks, firewood pieces and small packages of charcoal. A number of families also have kiosks and some households that have water taps sell water to their neighbours. The area that was targeted in Mbayani is the Gama area, where 150 households were electrified, representing approximately 1.5% of the households in Mbayani.

2.5.2 Sampling

Due to limitations in terms of time and finances, a sample survey was conducted in the target area and an attempt was made to develop a sample frame of the target population. The randomisation device that was initially to be used for selecting this sample was a table of random numbers. However, because the houses in the area are unplanned and not numbered, their order is not easily discernible hence it was difficult to use any definite probability sampling methods. Interviews were therefore conducted in every third house in a particular

cluster. The area was divided into four clusters to avoid incidences where one enumerator would interview households that had been interviewed by another enumerator.

2.5.3 Data collection

Due to problems encountered during the survey, only ESCOM's Marketing Manager who co-ordinated the Mbayani low cost electrification program, was interviewed for the supply side analysis. A structured questionnaire was used to gather the information required (Appendix 2).

A household survey was conducted to gather information from the user side and a total of 53 households interviewed using a structured questionnaire, developed by the author (Appendix 3). Interviewees were key household members of either gender or any household member over 21 years of age. Research assistants were trained for one week, and the questionnaire was pre-tested and modified in accordance with issues encountered during pre-testing. The author participated in the survey as an enumerator, provided in-field supervision and support and reviewed all questionnaires to ensure that research assistants were conducting the interviews to required standards. Responses from the questionnaire were later coded and the data analysed using Microsoft Excel Package with the Analyse-it extension, with a confidence limit of 95%.

The author also conducted two key informant interviews from community members who took key roles during implementation of the program. These interviews were in form of free but guided discussions aimed obtaining the experiences of the key informants and a literature review was used to gather data on South Africa.

All user side interviews, including the proceedings from the key informant interviews were done in the local language; Chichewa. The author then transcribed the interview proceedings and then translated the responses to English before entering the data in a data structure and processing the data, analysing it and discussing the findings.

2.6 Research challenges

One challenge experienced from the utility side was the bureaucracy surrounding releasing of utility data to the public. This resulted in delays which then resulted in rising costs of the study. The delays were exacerbated by the reluctance by some ESCOM employees to provide information on the utility. The second major challenge was the lack of data required for the study, even where utility employees were willing to provide the data. This was especially true for data relating specifically to the Mbayani low cost electrification program. As a result, certain aspects of the utility side assessments were either not done or done using proxy data. In other cases, data, in particular financial and technical performance data was collected from the electricity regulator rather than the utility. Latest data on the performance of the utility including ESCOM annual reports for 2000, 2001 and 2002 were not yet published and therefore

unavailable. In such cases, data from the 1999 annual report, which was the latest published data at this stage, was used, while in others, unpublished data from the regulator was used.

On the demand side, one challenge faced was the political connotations that the issue of electrification has in the area. As a result during the study, a number of the respondents were cautious as of the motives of the survey in view of the parliamentary and presidential elections that are to be held in 2004. People were also reluctant to answer questions for fear that they may lead to electricity disconnection in the area, for example, if they revealed that they had defaulted. In addition, most respondents 'wanted tangible results from the study' and wanted to know how the study would improve their livelihoods. Whilst the author desires that the study makes meaningful contribution to the quality of policy, services and livelihoods, there is no guarantee that the policymakers and responsible utility personnel will take up the findings and recommendations of the study. Some households were unwilling to answer income and expenditure related questions.

In order to deal with the demand side challenges, detailed explanations of the aims of the study were provided to the potential respondents before interviewing them and respondents were assured of the confidentiality of their responses. The respondents were given a choice to proceed with the interviews or not. Over 95% of households approached proceeded to answer the questions.

2.7 Possible sources of errors

A crucial part of the survey involved assessing income and expenditure patterns of households. Possible sources of error resulting from this aspect of the survey include the fact that up to 57% of the respondents were women because men were either at work or felt that women would answer to energy related questions better because they deal with household energy issues on a daily basis. However, most women were not in paid employment and do not know how much their husbands earn or how some of the household's expenses are allocated. In some cases, households felt that their expenditure patterns were a private matter and refused to provide this information. In yet other cases, some households inflated their expenditure to emphasize the high costs of living, while other households reduced their incomes and expenditures in an effort to underscore how poor they are.

The time of the study also coincided with a period of high political tensions, which may have affected the responses provided by some households. In addition, there seems to be tension between ESCOM and some newly electrified households because, according to Mbayani residents; ESCOM had disconnected some households without prior notification including households that had no arrears. This made some households suspicious of the 'true reasons

behind the survey' and may have resulted in households giving false information, some of which may have been hard to verify due to lack of records.

Lack of budgets and income and expenditure records meant that most expenditure data was estimated from memory, which may have led to distortions. In addition, there are non-monetary "incomes" that contribute to the livelihoods of household members but are not accounted for. These include garden produce, poultry and some households even have their own woodlots that provide firewood "free of charge". In other cases, expenditures are obscured by home-based income generating activities, as was the case in one household, where the respondent said their water bill was MK3, 500 per month. This household sells water to neighbouring households and water sales and consumption expenses are not separated.

Most of these possible sources of errors were dealt with using probing techniques and where probing techniques still yielded unreliable data, such households were excluded from the particular analysis. However, some discrepancies may not have been apparent. There were also obscure expenditures, such as help in form of cash or groceries sent to home villages to support relatives and friends, which is often irregular and hard to incorporate in the analysis.

CHAPTER 3: STUDY FINDINGS AND DISCUSSIONS

3. Introduction

This chapter presents findings of the study in two major sections. The first section presents supply side findings aimed at examining the processes of implementing the low cost electrification program in Mbayani in order to understand how such electrification strategies and processes might have affected the benefit and cost outcomes of the electrification program. The underlying themes of the benefits and costs study on the utility side include electrification financing, planning and the effect of the tariff design on the financial performance of the utility. The second section presents the findings of the demand side survey aimed at examining how the electrification strategies used in Mbayani affect the newly electrified households.

3.1 Supply side findings

3.1.1 Description and structure of the service provider

Established in 1965 under the Electricity Act (1965) the Electricity Supply Corporation (formerly Commission) of Malawi (ESCOM) dominates the Malawi electricity sector. ESCOM has a maximum installed capacity of 306 MW and generated a total of 1,128.5 GWh of electricity in 2002 (Potani, 2002). Up to 285 MW of ESCOM's installed capacity is hydro power while 15 MW is natural gas generation and 6.4 MW is diesel generated electricity.

ESCOM was restructured in 1998 as part of on-going power sector reforms, and is now a is now owned by the Malawi government, which owns 99% of the shares and the Malawi Development Corporation (MDC), which has 1% of the shares. It must be noted here that MDC is an investment arm of the government with a portfolio of investments, making ESCOM virtually fully owned by the government. The utility was also vertically separated into generation, transmission and supply "companies", having their own managers (Matinga, 2003). The supply company was sub-divided into three business units demarcated along regional administrative line, namely the Northern Electricity Supply, the Central Electricity Supply and the Southern Electricity Supply companies.

ESCOM is currently the only electricity service provider operating in Malawi, despite the fact that the electricity sub-sector was opened to private participation in 1998. The corporation is headed by a Chief Executive and has a deputy chief executive, a technical director and a financial director. Three of the four top executives (i.e. excluding the deputy chief executive) are on a management contract from Eskom of South Africa (Figure 3).

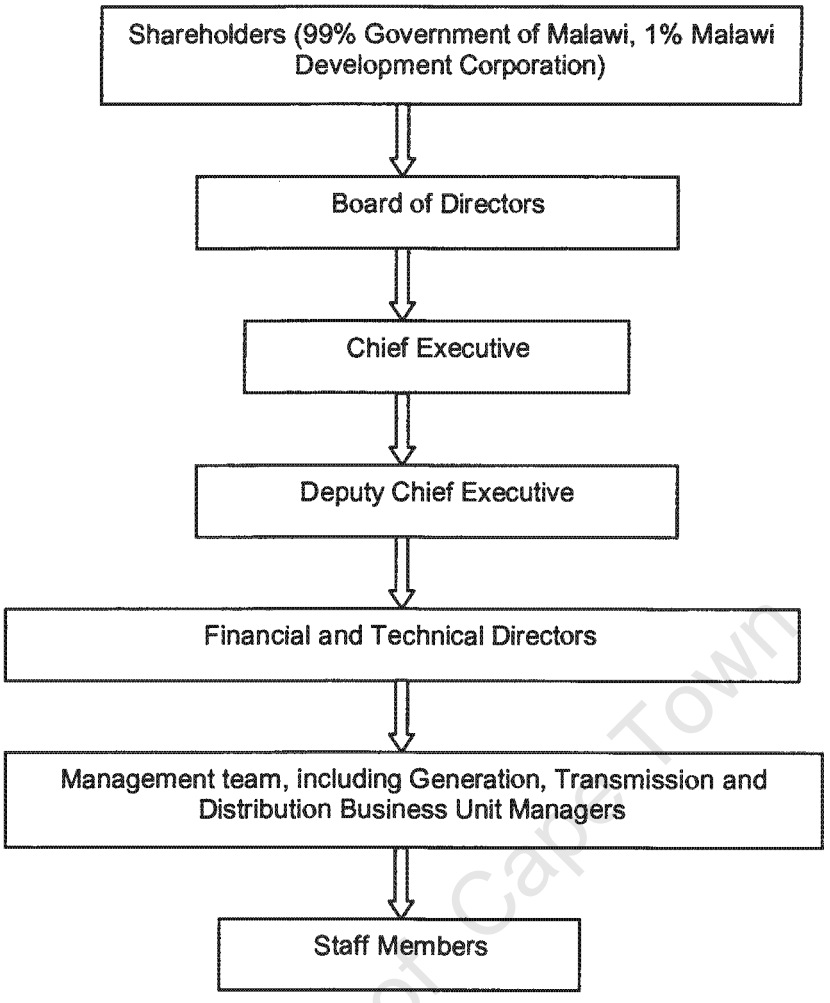


Figure 3: ESCOM's corporate and management structure

The low cost electrification process was carried out partly in response to numerous inquiries from poor households to have their homes electrified. Additionally, it was in response to government's call for ESCOM to increase access to electricity among poor households in line with the energy policy which aims at increasing electricity access from 4% of the Malawi population in 1998 to 10% by the year 2010 (Lungu, 2002).

3.1.2 Financing and planning issues

Financing for the Mbayani low cost electrification program was entirely from ESCOM's revenues and Mbayani had most of the infrastructure such as low voltage lines and a transformer in place. The capacity of the transformer installed in Mbayani was enough to transmit electricity to all households in Mbayani, yet for several years; only about five households had electricity in the project area (Kabwazi, Pers. Comm. 2003). Thus the available transmission infrastructure was being under-utilised and constituted a hidden cost to the utility. The prolonged under-utilisation of electricity infrastructure in Mbayani may be attributed to the high costs of connecting to the grid. This is compounded by the lack of pro-poor policies to

assist poor households in accessing electricity. Prior to the low cost electrification program, there was no set policy on low cost urban electrification in ESCOM or the DOE but the utility intends to develop such a policy after the pilot program in Mbayani (Kabwazi, Pers. Comm.2003).

According to the initial plan, the pilot program in Mbayani was a pre-cursor that would be extended to 24 areas and electrify 5000 households in 5 years (Mchulu, 2000:10). Before implementing the program, ESCOM carried out a program cost-benefit analysis, based on economic factors to assess the program's impact on the utility but did not carry out a technology comparative analysis (i.e. ESCOM considered compact ready boards only). ESCOM did not carry out any demand side needs assessment or any other demand side impact assessment in Mbayani or any other urban area in Malawi prior to the implementation of the program. The lack of research and detailed planning seems to be a result of both limited finances and lack of appreciation of the value of research in electrification programs (Case Study 1). In addition to the low levels of finances for research, ESCOM faces the dilemma of balancing the need to provide electricity services as commercial entities and the need to provide services for social benefits.

Case Study 1: Poor planning or conflicting priorities?

Mr Wiseman Kabwazi is the Marketing Manager for ESCOM and coordinated the Mbayani electrification program. His sentiments on the program provide useful insights on planning issues for pro-poor electrification programs;

> We did not see the importance of researching compact ready boards before implementing them. We sat down and decided we were going to use this method in the program and went ahead with it. The Department of Energy officials have seen the project and are so impressed that they want a similar program for the Malawi Rural Electrification Program. To us there is no doubt that the people are benefiting from the project. We don't have the time or money to do research because we have enough information and we don't have a specialised research department. ESCOM is a poor company and cannot afford some of these things [i.e. research].

Although the benefits to people are 'seen by the utility' the benefits to the utility are not very clear.

> This is a social program and is not profitable to ESCOM. In addition, we now have doubts on whether the people in Mbayani are poor or not. The moment they get the electricity, they are improving their houses, buying electrical appliances and want to use the electricity for welding and other high consumption activities. Now they want to change to conventional electricity connections. This is why we think this technology is more suitable for rural areas than for urban areas

Case study 1 illustrates that the limited focus in planning was a result of the lack of appreciation of research and demonstrates the traditional top-down approach that ESCOM has

used in the past decades when electrifying households. This resulted in cost-benefit analysis focussing on supply side implications and disregarding the users' needs. In most cases, the failure of top-down approaches has resulted from limited positive response from target users who feel their needs are not addressed and a lack of a sense of ownership among the target population. Lack of finances may also have contributed to ESCOM's preference of the traditional top-down approach. Although ESCOM is profitable, its profits are eroded due to the large portion of foreign currency denominated costs and debt servicing; hence public benefits are relegated in favour of commercial gains.

3.1.3 Assessment of the supply options and technology used

The transmission system used was the same as that used in conventional electrification since this was not a completely separate program, hence low voltage 11KV lines were used. The major difference in technology use was at household level where compact ready boards were used instead of conventional wiring. Each of the compact ready boards has four socket outlets and one bulb attached to the compact ready board unit. The socket outlets are marked in writing and have accompanying pictures, showing which electrical appliance to use on a particular socket. The electrical appliances that are indicated include a two-plate hotplate, an iron, a radio, a television, refrigerator and a bulb. There are no meters for recording electricity consumption. Each compact ready board has a limited current supply of 15Amps. Although Poly Vinyl Chloride (PVC) conduits have been used in the majority of the households, enumerators noticed that there were households that were wired without conduits. Some residents claim that during the implementation phase, some of the labourers were selling the PVC pipes to hardware kiosks, builders and other interested persons.

Since most of the houses electrified under this program are built with mud and un-burnt bricks, their walls are too fragile to consider conventional wiring. In addition, conventional wiring would increase the costs of electrification for the households. To address these two problems, a bracket is mounted outside the house, and insulated wiring is connected via the bracket and into the house (Picture 1) and to the compact ready board unit.

While ESCOM is the service provider and responsible for the program in Mbayani, installation of compact ready boards was sub-contracted to an engineering firm called Intertec, which made the 150 installations over a period of about two months. Intertec has since closed its operations in the country. It was therefore impossible to obtain data from the company on its electrification benefits, costs and experiences.

Picture 1: A bracket attached to a house thatched with grass and plastic sheets.

3.1.4 Electricity tariffs and cost recovery

Electricity tariffs for the Mbayani electrification program are based on the conventional domestic tariff structure (Table 5).

Units (kWh) per month	*Fixed charge per month in MK*	*Unit charge in MK/kWh*
First 30 units	72.96	1.57
In excess of 30 units per month and less than 750 units per month		2.29
In excess of 750 units per month		3.25

Table 5: Domestic tariff structure in February, 2003
Source: ESCOM, 2003

Since households with compact ready boards are not fitted with meters, a fixed rate tariff is used to bill customers. Tariff was initially set at MK410 per household per month at the onset of the program in June 2001 and had risen to MK550 per household per month by the time the survey was carried out in 2003. This fixed monthly payment includes a contribution of MK85 towards cost recovery of compact ready board costs. Only one tariff adjustment has been made from the time the program was implemented to the time of the study although domestic tariffs have changed more than once. This signifies that the tariff in Mbayani is not strictly linked to the conventional domestic tariff and it was not clear from the interviews, how this adjustment was decided.

Each compact ready board unit cost the utility an average of MK3, 000 and households were charged MK5, 700 per connection which is to be paid over a period of five years (Kabwazi, Pers. Comm.2003). Although information on the exact overall costs was unavailable from ESCOM, newspaper reports based on interviews with ESCOM officials at the onset of the program reported that the program's costs were at an estimated MK2 million (Mchulu, 2000:1-3).

Although there is no data on cost recovery, ESCOM's Marketing Manager estimated 40% of the compact ready board costs have been recovered, but that the return on investment is very low (Kabwazi, Pers. Comm. 2003). Meanwhile, ESCOM has concluded that although the compact ready board technology and current limited supply are good supply options for urban poor households, they are better suited to rural areas rather than urban areas because poor urban households want to use their electricity for a wider range of activities, including SMEs especially welding and spray painting (Kabwazi, Pers. Comm. 2003). This conclusion is based on anecdotal evidence since a progress analysis has not been conducted yet.

The payments for these compact ready boards are part of the monthly tariff and therefore full recovery of their costs depends on the households' ability to pay for their electricity bills for the entire 5 years. The fact that non-payment of bills results in discontinuity of electricity supply may be an affective risk hedging mechanism that motivates households to pay their bills and it is therefore likely that all the costs will eventually be recovered.

3.1.5 Effect of tariff design on utility's revenues

The lack of program specific data hindered detailed analysis of effects of the tariff design on the utility's revenues and profitability. However, analysis of financial data from the electricity regulator shows that the utility has maintained its costs at an average of 60% of its revenue and a profitability averaging 34.5% between 1990 and 2000 (Table 6). In addition, an analysis of the customer composition based on 1999 data shows that revenues from the entire domestic sector contribute 16% of all revenues collected by the utility and the power sold to the domestic sector represents 29% of all the power sold by the utility (ESCOM, 1999). It is therefore unlikely that revenues and profitability of the utility are adversely impacted by the tariff design of Mbayani low cost electrification program since it targeted 150 households only while ESCOM has a customer base of about 110,000 customers. Also in the short term, households have fewer appliances and so their electricity consumption levels are low.

	1989 /90	1990/ 91	1991/ 92	1992/ 93	1993/ 94	1994/ 95	1995/ 96	1996/ 97	1997/ 98	1998/ 99
Revenue/Unit (T/kWh)	11.5	12.5	12.8	19.8	21.1	29.9	48.9	61.8	84.1	133.5
Cost/Unit (T/kWh)	7.4	7.8	7.8	9.3	9.2	15.2	25.8	39.3	61.7	101.3
% of Cost/Revenue	65%	63%	61%	47%	44%	51%	53%	64%	73%	76%
Profitability (%)	38	36	44	38	45	9	34.1	35	24	42

Table 6: Revenue, costs and profitability of electricity in ESCOM from 1989 to 1999
Source: GoM and JICA,2002, Potani 2002

Adopting the tariff design in the Mbayani electrification program for urban electrification programs on a larger scale would however have negative implications on revenue intake and profitability of ESCOM since the flat rate tariff design used in Mbayani is not responsive to changes in consumption. There is therefore need to reconsider tariff design in pro-poor urban electrification initiatives.

In addition, households are likely to acquire more appliances and it is likely that the utility will experience negative returns from increasing consumption in the program area. Furthermore, the monthly flat rate tariff design provides no incentive for efficient use of electricity and may exacerbate revenue losses as real consumption exceeds the consumption level upon which the monthly flat tariff was based. For the utility, increase in consumption by consumers results in decreased revenues since the revenue is constant (Figure 4).

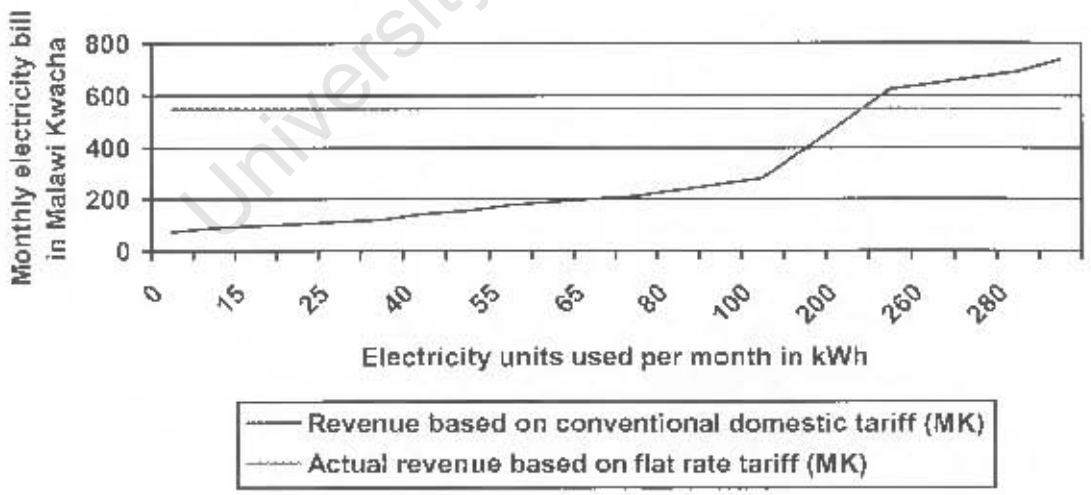


Figure 4: Model depicting revenue trends of conventional domestic tariff versus flat rate tariffs

The lack of detailed research may have contributed to the implementation of a tariff structure that has negative implications on the utility's revenue for wider scale applications and for the long term.

3.1.6 Supply side summary of findings

Based on the limited data from the utility, it may be concluded that, major weaknesses of the Mbayani electrification program have been the lack of detailed research and planning and a poor tariff design. This has resulted in implementation of a program that has no substantial benefits for the supply side. The costs that the program imposes on the utility exceed the benefits that the utility realises. Nevertheless, unless the program is carried out on a larger scale, any negative impacts on financial performance of the utility are minimal and not a threat to the financial performance of ESCOM.

It is interesting to note that a decision has been made (albeit tentatively), based on anecdotal evidence not to proceed with compact ready board low cost electrification programs in urban areas, before carrying out an in-depth analysis of the impact of the program on users' livelihoods and investigating the bottle-necks of the program design to find solutions. As with planning at the onset of the program, ESCOM illustrates its preference for a top-down approach and limited research in finding solutions.

3.2 Demand side findings

This section presents findings from the demand side survey and aims at examining how the electrification program affects the newly electrified households. The section is presented in 8 sub-sections, starting with a section on description of the sample and a discussion on the program launch. The following sub-sections then deal with the following findings and discussions;

- Household incomes.
- Key household expenditures.
- Electricity payment mode and terms under the low cost program.
- Fuel use before and after electrification.
- Appliance acquisition and usage after electrification.
- The impact that electrification has made on SMEs in Mbayani.
- Users' perceptions of compact board electricity.

The aim of the demand side survey is to investigate the benefits and costs that accrue to users of electricity in Mbayani. Due to some invalid or unreliable responses, in certain sections, the number of respondents varies. This is taken into consideration in the analysis and so the analysis is based on the valid sample only.

3.2.1 Sample description and program launch

An estimated 150 households were electrified in Mbayani in June 2001 using compact ready boards and a total of 53 households were interviewed for the study, representing 35% of these newly electrified households. In terms of the gender distribution of the respondents, 57% of the respondents were female household members including either mothers or wives and daughters over the age of 21, while 43% were male household members including either fathers or husbands and sons over the age of 21 (Table 7).

Respondent	*Position in household*	*Percentage of sample population*
Female	Mother/Wife	53
	Daughter	4
Male	Father/Husband	30
	Son	13
Total		100%

Table 7: Respondents by gender and position in household.

Of the 53 households interviewed, 83% were male-headed households while 13% were female headed and 4% were headed by both male and female (Table 8).

Household Head	*Number*	*Percentage of sample population*
Male	44	83
Female	7	13
Both	2	4
Total	53	100%

Table 8 : Household headship by gender

In terms of household size, the smallest households had occupancy of 2 persons per household while the largest households had 10 persons per household. The average household size was 6 persons per household (Figure 5).

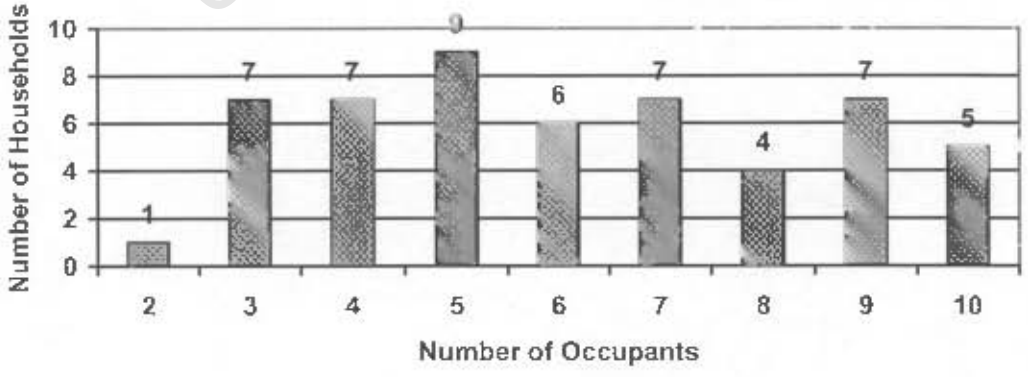


Figure 5: Distribution of number of household occupants in Mbayani

The average household size in sampled population in Mbayani is 50% higher than the average household size in Malawi, which is estimated at 4 persons per household (NSO, 1998:14). Higher household sizes are typical in poor households in urban areas because such households are more likely to foster persons from extended families.

In terms of house ownership, up to 87% of the houses are owned by the householders while 11% were rented. Only one respondent reported that he was in the process of buying the house he lived in. The high level of house ownership in Mbayani is consistent with household ownership patterns among the poor in Malawi. Up to 86% of the poor own their houses in Malawi (NEC, 2000). In Mbayani the high rate of house ownership may be attributed partly to the fact that the poor often live in unplanned areas and their plots are obtained either "free of charge" or at lower prices from traditional leaders or community-elected leaders. Some of the residents of the township were given pieces of land "free of charge" by the colonial era government after being displaced from what are now the city centre and the low and medium density suburbs. Mbayani residents often build their own houses or acquire labour from within the community and improve the houses over a period of time.

It should be noted however that most of the poor do not have legal tenure and at a national level, only 15.8% of the houses are permanent, while 18.4% are semi-permanent and 65.8% are traditional and not permanent (NSO, 1998). Most houses in the sampled area in Mbayani would be classified as semi-permanent, having been constructed using un-burnt mud bricks.

Before implementing the low cost electrification program, ESCOM held a launch meeting to introduce the program to the community. Of the interviewed household sample, up to 68% of the respondents attended the launch meeting. Of the 32% that did not attend the launch meeting, 6% were tenants who had rented their homes after the electricity had already been installed. Of those that attended the launch meeting, 55% were male, while 45% were female. Up to 86% of those that attended the launch meeting understood the program specifications including connection costs, tariffs, capacity constraints and uses, which translates into 58.5% of the total sample interviewed (Table 9). A total of 65% of those that did not attend the launch meeting understood the program provisions, translating into 21% of the sample household population.

	Understand	*Did not understand*	*Total*
Attended	58.5%	9.4%	68%
Did not attend	21%	11%	32%
Total	79%	21%	100%

Table 9: Attendance of launch meeting and understanding of program specifics

In total 79% of the respondents understood the provisions of the electrification program while 21% of the respondents did not understand some aspects of the electrification program.

There is a higher level of understanding of how to use electricity and its other provisions by those that attended the launch meetings compared to those that did not attend launch meetings. This indicates the need for dialogue to ensure understanding, which may contribute to households benefiting more fully from their newly acquired electricity.

3.2.2 Household incomes in Mbayani

This section discusses findings related to incomes in the sampled households in Mbayani. Some households were unwilling to reveal their incomes because they consider them private, while other respondents were unaware of their household incomes if they were not the income earners in the household. As a result, only 37 respondents, representing 70% of the sampled households revealed their incomes and hence all household incomes related analyses are examined based on the specific population valid for this section. The purpose of the section is to understand income flow patterns, income levels and distribution patterns as a basis for understanding the effects that changes in fuel use can have on the electrified households and how these relate to household incomes.

Income flow patterns

Although some income flows patterns in the sampled households are not monthly because of their varying sources, households generally categorised them in monthly terms.

The survey found that the sampled households in Mbayani often have more than one source of income. In Mbayani, main sources of income include employment, food sales, house rentals, sale of imported second hand clothes, kiosks, sale of charcoal, sale of water and remittances. On average, households have 2 sources of income per household and the highest number of sources of income per household was 6 (Figure 6).

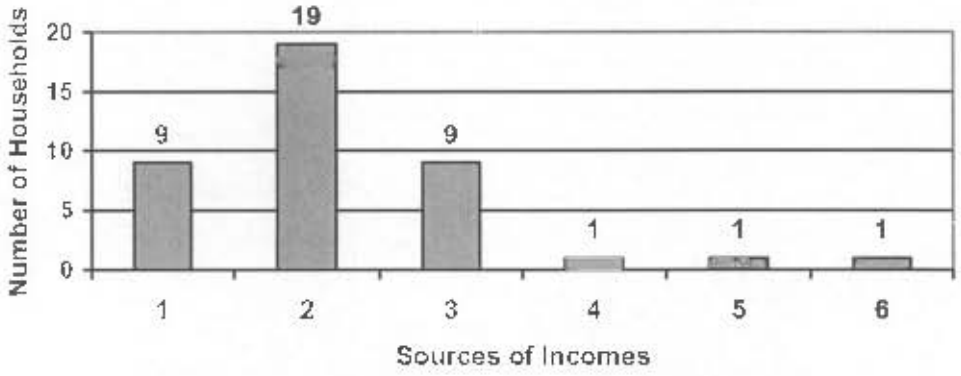


Figure 6: Number of sources of income in valid sampled households in Mbayani

Average household incomes in Mbayani

The average monthly income in the valid sub-sample of 37 households was MK5, 478.24. The highest income recorded was MK33, 000 per household per month whilst the lowest average monthly income was MK300 per household (Figure 7).

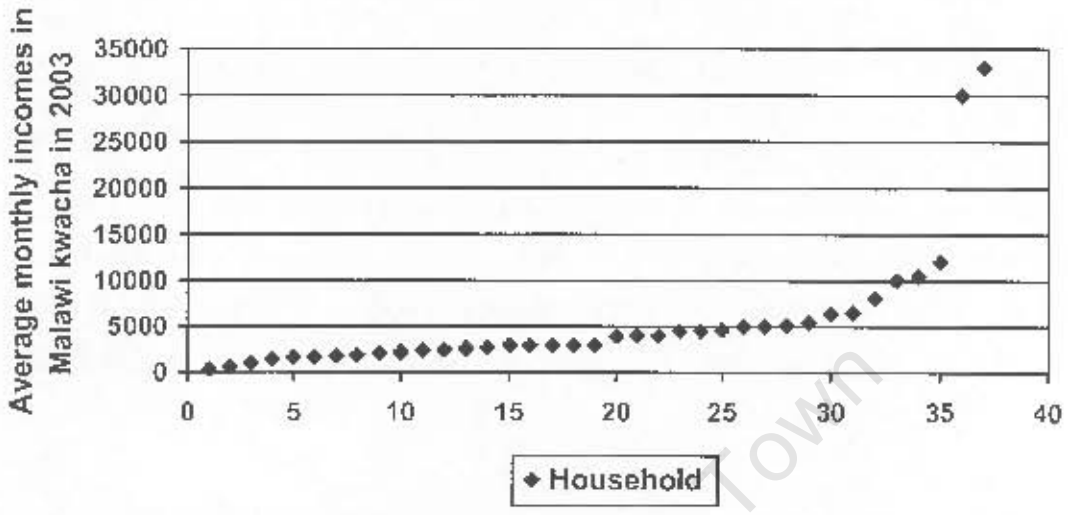


Figure 7: Monthly average incomes in valid sampled households in Mbayani

Of the 37 households that revealed their incomes, 3 were found to be outliers and two were extreme outliers. The presence of outliers and extreme outliers in the data can be attributed to either over estimation or to multiple income sources as exemplified by one of the two extreme outliers, who had 6 sources of income including two micro-enterprises, remittances and a salary. Assessing the income levels without the 2 extreme outliers reduced the average income to MK3, 991.29 with a standard deviation of 2762.04, which is more realistic since 45% of households in Blantyre City have monthly incomes that are less or equal to MK4, 000 while only 2% receive incomes of between MK30, 000 and MK35, 0000 (GoM, 2002:42), the bracket within which the two extreme outliers occur.

Income distribution

Wide deviations were found in the income patterns of the households interviewed and the standard deviation for the monthly incomes of the 37 valid households was 6, 862.81. Up 73% of the valid sampled households were within the first quintile, with monthly incomes that are less than the average income of MK5, 478.24 (Figure 8) while 5% had incomes of about 6 times the average income of the 37 valid respondents. The wide variation in incomes is attributed to the wide variations in income sources and flow patterns.

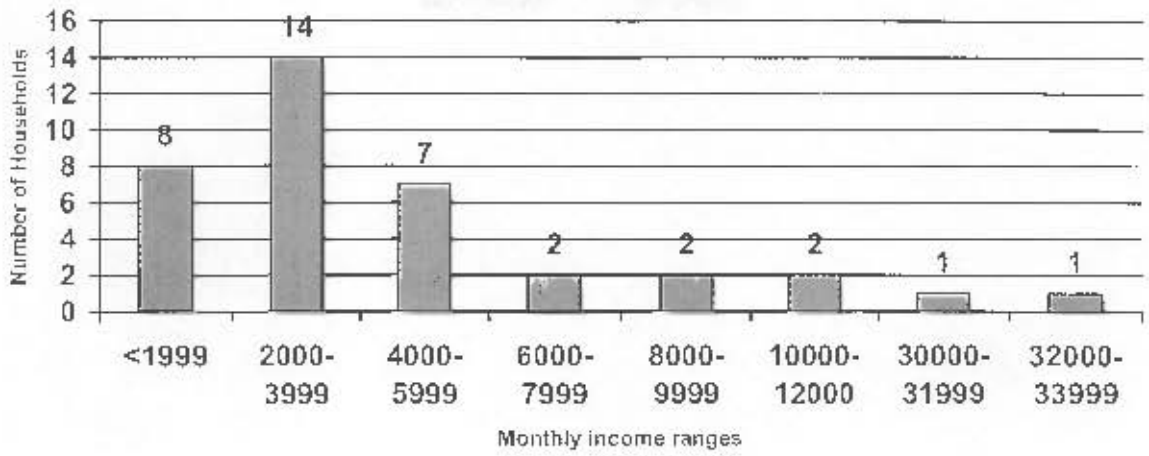


Figure 8: Income distribution in Mbayani

3.2.3 Household expenditures

The aim of this section is to identify the key expenses that households have and examine the burden that fuel expenses impose on the household budget. It also aims at assessing how the burden that fuel expenses impose on the household budget has changed after electrification.

The key expenditures that the questionnaire investigated included energy expenditures, food, water, health, school fees and transportation. The study found that some of the key expenditures were monthly while others were not monthly. The non-monthly key expenditures are identified and acknowledged but have been excluded from the energy burden analysis because the burden analysis is based on a monthly basis for ease of analysis.

Due to the low and sometimes erratic incomes, the people of Mbayani do not have set budgets and have few planned expenses. This means that expenditures data was estimated and based on memory rather than written records, which may introduce errors. However, the relative consistency of the expenditures and costs of items suggests that the estimates given by the respondents were fairly accurate. This is another reason why energy burden analysis is based on monthly expenses which are easier to remember and estimate compared to non-monthly expenses.

Non-monthly expenditures

The study found that school fee expenses were erratic and mostly bi-annual or tri-annual. In most cases, school-going children attended government primary schools for which they pay a school fund of MK8 per trimester. Some school children however attend private schools[2] and

[2] Most of these private schools are not accredited and their school fees vary from monthly payments to tri-annual payments. The amount of the school fees also depends on the quality of education and qualifications of teachers in each school.

secondary schools, for which they paid an average of MK645.50 per child per term in school fees before electrification, and an average of MK1, 024.44 per child per term after electrification.

Most transport expenses were invalid because the people in Mbayani area are close to the city centre and their places of employment as well as a major government hospital and since their incomes are low, they walk to their places of employment, to the market and the hospital except in some cases of medical emergencies. Only three households could respond to the question of transport expenses but reported that these expenses were erratic and not always on a monthly basis because during some months, they walked to their work places. The households spent an average of MK188.46 per household per month on transport before electrification and an average of MK300 per household per month after electrification. Due to the inconsistencies in school fees and transport expenses, these expenses have been excluded from further analysis.

On health expenses, it was found that almost all households visit the free government hospital and so did not have valid health expenses. However, a number of households stated that health was a major hidden cost and households often spend money on health related items including visits to private health practitioners, herbalists and also spend money buying medicines on the streets because the hospitals rarely have medicine in stock or for transporting patients to hospitals and clinics. Other health related expenses were for visits to sick family members and friends in hospital. Some of these medical expenses are not accounted for because of the belief that you cannot put a cost to human life, which includes accounting for health expenses.

Monthly food, fuel and water expenditures

The interviewed households spent an average of MK1, 345.31 per household per month on food before electrification. This increased by 64% to a monthly average of MK2, 204.69 per household after electrification. It should however be noted that in this case, the food item accounted for most often was maize meal used to make the traditional mealie based staple food locally known as "*nsima*". "*Nsima*" is normally accompanied by a protein food such as meat, beef, eggs, fish and vegetables, locally known as "*ndiwo*". The expenses for the "*ndiwo*" are harder to estimate because they change often, depending on purchasing patterns and practices of the household at a particular time. In some cases households have gardens and rare poultry, whose produce they sometimes use as "*ndiwo*". Food expenditure patterns also change depending on the season, with a decrease in prices of maize and maize flour soon after harvest between April and June and a decrease in expenses of "*ndiwo*" during the rainy season between December and February because people supplement their diets with wild vegetables.

The main fuels used in Mbayani before electrification, were charcoal, firewood, dry cells or car batteries and paraffin. Average monthly fuel expenditure per household was MK859.30 before electrification and this increased by 6% to MK910.10 after electrification. After electrification, major fuels were electricity, charcoal and firewood while paraffin, was a minor fuel, mainly used in emergencies or to start charcoal braziers. Few households also used dry cell and car batteries after electrification.

All the households interviewed did not have in-house plumbing. Few households had one tap outside their homes, but most households buy tap water from water kiosks or from households that have taps and sell water in the neighbourhood. Some households also economise by using the water they buy for drinking and cooking purposes and drawing water for bathing and washing from a river that runs across the township. Before electrification, households spent an average of MK306.67 per household per month on water, whilst after electrification, households' monthly expenditure on water increased by 64.5% to an average of MK504.33 per household on water.

The fuel expenditures' increase of 6% after electrification can be attributed to overall increases in fuel costs that occurred between 2001 and 2003. Another contributing factor is that, with the exception of lighting where electricity is used almost exclusively (paraffin and candles are used in cases of blackouts), most households are using electricity as an additional fuel and rather than a full substitute to previously used fuels. This means that other fuel expenses have been reduced because of their reduced share in the total household fuels composition but have not been eliminated and their increasing costs contribute to increased fuel expenditure. The use of electricity as an additional fuel rather than a substituting fuel is partly attributed to limited incomes that hinder households from purchasing appliances and to unreliability of electricity and appliances.

Compared to other monthly household expenses such as food and water, which increased by 64% and 64.5% respectively between the same period from 2001 to 2003, the 6% increase in fuel expenses is minor (Figure 9) and may be considered as a positive result of electrification. Meanwhile, overall inflation in Malawi has been at an average of 16%, with non-food inflation at 18% and food inflation at 14% between 2001 and February 2003 (RBM, 2003). Urban inflation however was higher in 2001 and 2002 at 21.7% and 19.8% respectively (NSO, 2003). The fact that fuel expenses were far below inflation levels indicates that households were experiencing savings due to changes from biomass fuel use to electricity. The high increases in food and water expenses which are far above the inflation rates can be attributed to the fact that scarcity of these commodities lead to shady markets which often charge exorbitant prices.

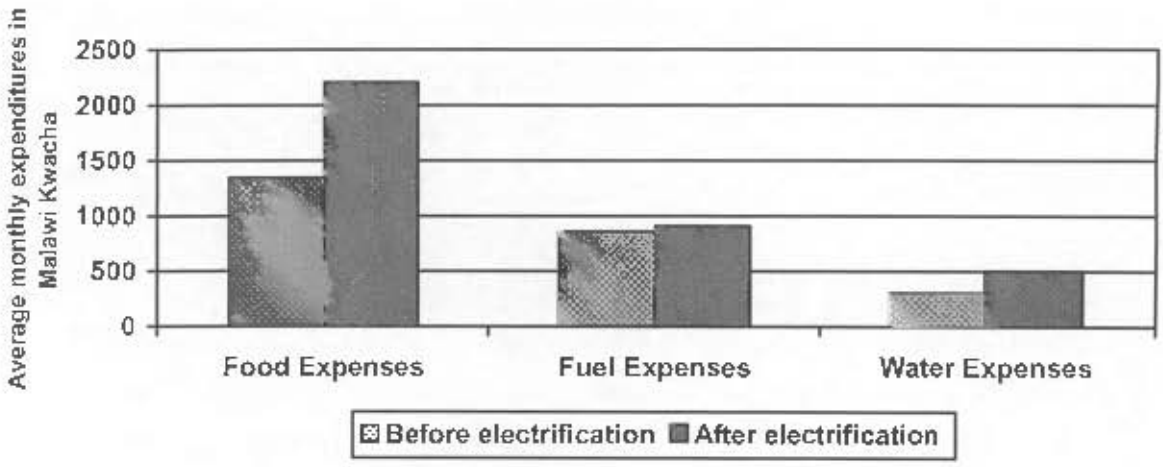


Figure 9: Comparison of essential expenses trends before and after electrification

In relation to essential monthly expenses of food, fuel and water, food expenses were 54% of the total essential monthly household expenditures before electrification, while fuel and water expenses constituted 34% and 12% respectively (Figure 10) of total essential monthly household expenditures. After electrification, the food expenses share of the three essential monthly expenditures increased from 54% to 61%. Fuel expenses decreased from 34% to 25% of essential monthly expenses after electrification, while water constituted 14% of monthly essential expenditures after electrification (Figure 10).

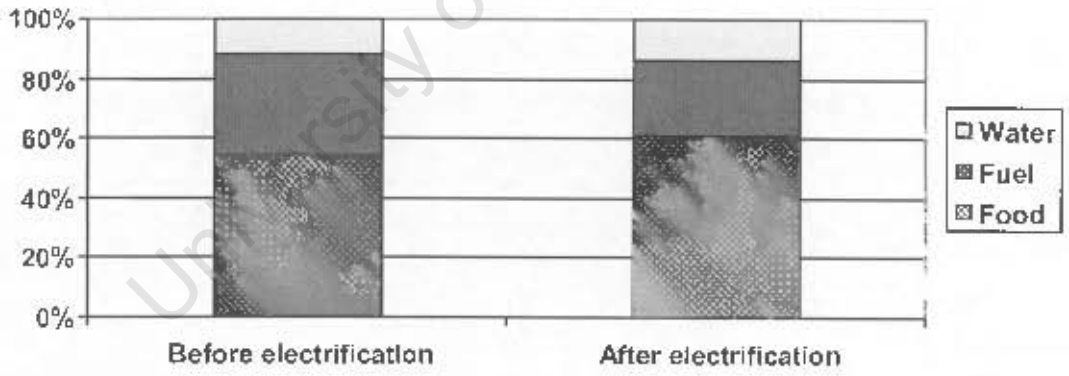


Figure 10: Shares of essential monthly expenditures before and after electrification

Thus overall, expenditure on food, in relation to expenditure on fuel and water, increased by 7%, while expenditure on fuel, in relation to food and water, decreased by 9% in terms of shares and expenditure on water in terms of shares of essential monthly expenses of food and fuels, increased by 2%. It should however be recognised that the increases in these expenses are also affected by inflations and indicate increasing costs of living.

The changes in fuel expenses patterns in relation to key monthly expenditures of food and water imply that there is a decreased burden from fuel expenses on the household budget and that there are savings from fuels expenditures that may have been redistributed to other essential household expenses such as food and water. The low cost electrification of households therefore has the potential to improve the wellbeing including nutritional status and health status of households if the households use the money saved to buy better or more types of food and to buy better quality water.

Households in Mbayani spent an average of up to 22% of their household budgets on fuels before electrification whilst after electrification; the households spent an average of 17% of their household budgets on fuels. This implies that under the current tariff regime, use of electricity has reduced the energy burden, which is a benefit to the electrified households.

3.2.3.1 Individual fuel expenses trends before and after electrification.

The following sub-section is a discussion on the fuel expenses in terms of individual fuel's contribution to household's energy budget. It is aimed at assessing the effect of introducing electricity on individual fuel expenses. The study found that with the exception of electricity, all other fuel expenses decreased with the introduction of electricity.

Expenses share by individual fuels

The largest overall decreases in fuel expenses were observed where the majority of households switched to electricity. These include dry cells expenses which decreased by 93% after electrification, and paraffin expenses for lighting which decreased by 75.5% after electrification while car batteries expenses decreased by 70% after electrification (Table 10). The car batteries were bought over different time periods and their price ranged from a minimum of MK150 and a maximum of MK950. Apart from the time when the battery was bought, the price of the car batteries was dependent on whether or not the battery was new or second hand when it was bought, its make and the country of origin of the battery and whether it was bought at a local market or a shop. The expenses on dry cells and car batteries after electrification are a result of few households that use battery operated radios for fear that their radios will get damaged with electricity or because their radios may not be adaptable to mains electricity. While all households have switched to electricity, the decrease in paraffin expenses is not 100% because households buy paraffin for emergency lighting during power failure and for igniting cooking fires. The only increase in fuel expenses was for electricity, which is attributed to the fact that there were virtually no electricity expenses before electrification. Only one household occasionally used diesel generated electricity before electrification and this was used in combination with paraffin for lighting and a car battery for media applications. It

should be noted that since households can use either one fuel or another, for example dry cells or car batteries or a combination of fuels such as firewood and charcoal, the average fuel expenditure per household in Table 10 is based on real fuel expenses in each household analysed and so the fuel expenses do not add up to the average fuel expenditure per household of MK859.30 per household per month before electrification and MK910.91 per month after electrification, discussed before in section 3.2.3 under the sub-heading "monthly fuel expenditures".

Fuel	*Charcoal*	*Firewood*	*Paraffin*	*Dry Cells*	*Electricity*	*Car batteries*
Average household expense before electrification (MK)	538.80	351.73	116.16	168.38	§	91.35
Average household expense after electrification (MK)	389.86	210.85	28.43	11.50	564.76	27.51
Net change in fuel expense after electrification (MK)	-148.94	-140.88	-87.73	-156.88	564.76	-63.54
Percentage change	27.64%	-40.05%	-75.53%	-93.17%	100%	-69.80%

Table 10: Fuel expenditure before and after electrification in Mbayani

Note - § Expenditure data from the household which occasionally used diesel generated electricity before electrification was unreliable and has been excluded from the analysis

The trend in savings shows that highest savings are made with the shift from dry cells to electricity, followed by the shift from charcoal and firewood to electricity. However, since dry cells are almost fully substituted while more people still use charcoal and firewood, this implies that significant savings would be made if charcoal and firewood were substituted with electricity. The fact that high savings in terms of percentage savings are made in when households change from using dry cells and paraffin are partly attributed to the fact that most of the related services that dry cells and paraffin offer have been substituted with use of electricity. This may be linked to the related cost of the appliances involved (i.e. radio and light bulbs).

Expenses share by general applications

Before electrification, the largest share of the fuel budget was spent on thermal applications, encompassing use of charcoal and firewood for cooking, water heating and space heating, which made up about 65% of all monthly fuel expenses (Figure 11). Media applications including radios and television, which were powered by dry cells and car batteries accounted for about 18% of all monthly fuel expenses, while paraffin mainly used for lighting accounted for almost 17% of the household fuels budget.

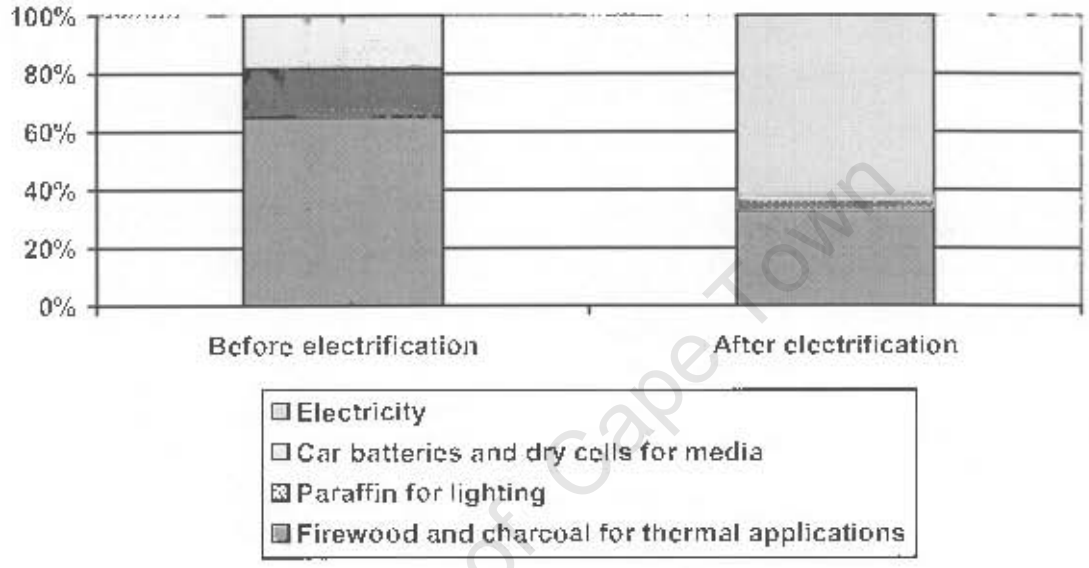


Figure 11: Shares of expenses by general applications before and after electrification

After electrification the largest share of fuel expenses was for electricity, which encompasses thermal, lighting and media applications. Electricity accounted for 62% of the expenditure share while the expenditure share for charcoal for thermal application decreased to 33%. The share of paraffin expenses used mostly for emergency lighting and igniting fires decreased to 3% while the share of expenses for dry cells and car batteries used for media applications decreased to 2%.

The presence of charcoal expenses, paraffin, dry cells and car batteries after electrification indicate use of multiple fuels, signifying that there are barriers hindering households from switching to electricity once their homes are electrified.

Since the largest share of the fuels budget before electrification is spent on thermal applications and electricity can fully substitute all applications, more cash savings would occur where thermal applications especially use of charcoal and firewood are fully (or almost fully) substituted with electricity use. While the majority of the households have shifted to electricity use for lighting and media applications, the existence of higher levels of charcoal and firewood

use after electrification indicate the need for special interventions to assist certain households to shift to electricity use in thermal applications.

Fuel expenses by household groupings

The survey showed that before electrification, 26.5% of the sampled households spent between MK200 and MK500 per month on fuels, while 35% of the sampled households spent between MK501 and MK1000 per month and 8% of the households spent between MK2, 001 and MK2500 per month on fuels (Figure 12). After electrification, only 6% of the population spent between MK200 and MK500 per month on fuels, while 64% of the population spent between MK501 and MK1000 for their fuels needs and 5% the households spent between MK2, 000 and MK2, 500 for their fuel needs (Figure 12)

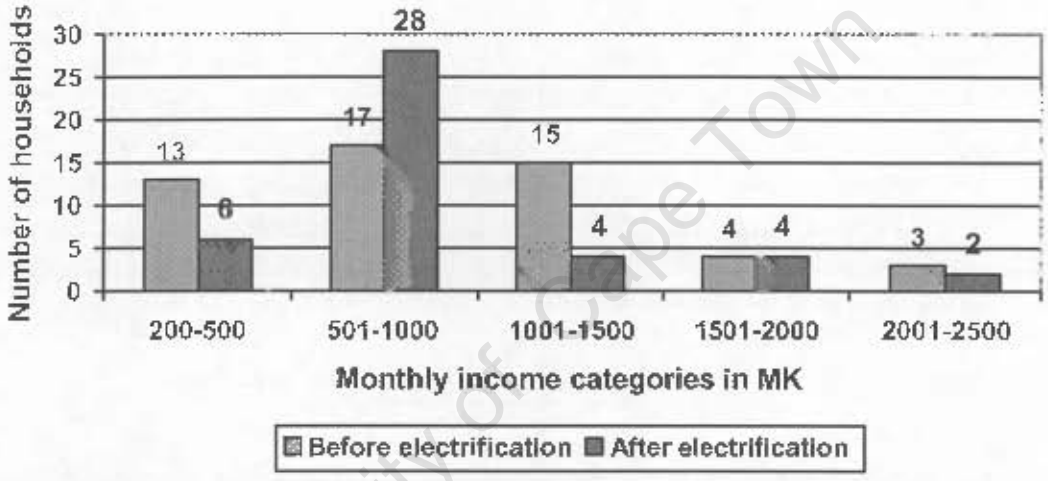


Figure 12: Fuel expenses quintiles before and after electrification in sampled households in Mbayani

In an ideal situation where all households are using electricity exclusively after electrification, almost every household would have been spending about MK550 per month on fuel. The distribution in Figure 12 indicates that some households who were paying less for fuels are now paying more. This is attributed to the fact that some households have not fully substituted other fuels with electricity. As a result of this, these households are paying for electricity and other fuels, thereby increasing their energy bill after electrification. The distribution also signifies that other households are paying less than the designated monthly tariff of MK550. However, certain households are paying the designated MK550 or more but still use other fuels, hence their fuel bills exceed MK550. The distribution pattern in Figure 12 also implies that the percentage of households spending between 0 and MK1000 has increased after electrification and overall, there is a more even distribution in fuels expenditure since most of the households are spending between MK501 and MK1, 000. Thus in terms of fuels expenditure, households are more "equal" after electrification than before, a fact that implies that introduction of electricity in these households in Mbayani has implications on intra-household and inter-

household resource redistribution and allocation. The fact that fewer households spent more than MK1, 000 per month on fuels after electrification compared to before electrification is an indication that some households that were previously spending more than MK1, 000 per month on fuels are experiencing cash savings on fuel expenses resulting from electrification.

3.2.4 Electricity payment in Mbayani

The following section examines terms of payments for electricity under the low cost electrification program. It assesses the electricity connection costs to consumers, the tariffs paid and mode and frequency of electricity bills. The discussion is aimed at understanding how the tariff design and its terms of payments affect households in terms of ease of payment and household energy budget control.

Hardware and connection costs

The respondents verified that at the onset of the project in June 2001, the cost of the compact ready board unit was MK5, 700 and that its costs are paid as part of the tariff on a monthly basis and are amortised over a period of 5 years. The connection charge was MK500 per household, compared to a connection charge of MK1,750[3] for conventional customers that are less than 500m from the nearest connection point and as much as MK50, 000 or more for conventional domestic customers that are more than 500m from the nearest connection point. In addition, consumers were not required to contribute to the costs of the transformer, which is the requirement if a customer is not within reasonable distance from the transformer. The amortisation of upfront costs is one of the aspects of the program that consumers feel is a benefit of the program design as reflected by one respondent's comment;

> For the poor, this electricity is good because we now have what we could have never have afforded. Who can afford a transformer among us?

The amortisation of electrification costs is an excellent method for increasing access to electricity in poor urban areas since it reduces the financial pressures that upfront costs impose on the poor households.

Tariffs and billing

At the onset of the program in June, 2001, a monthly flat rate tariff was set at MK410 per household, of which, MK325 was for consumption of the electricity whilst MK85 was the payment for the cost of compact ready board unit. The tariff was later increased and stood at MK550 per household per month at the time of the survey. It should be noted however that tariffs for conventional customers have changed several times between 2001 and 2003, with one decrease in August 2001. These changes however, have not triggered corresponding

[3] Introduced in 2002 under a program called Namagetsi.

changes in the tariff used in Mbayani, signifying that the tariff in Mbayani is not strictly linked to the conventional domestic tariff.

The study however found that the actual amounts that households pay to the utility vary (Figure 13), with one extreme outlier on the upper end paying MK1, 500 per month. According to the household head, they had started paying MK1, 500 per month when their financial situation improved so as to 'get rid of the compact ready board debt as soon as possible'. Another extreme outlier on the lower end was a household that was paying MK200 per month because they could not afford to pay MK550 per month.

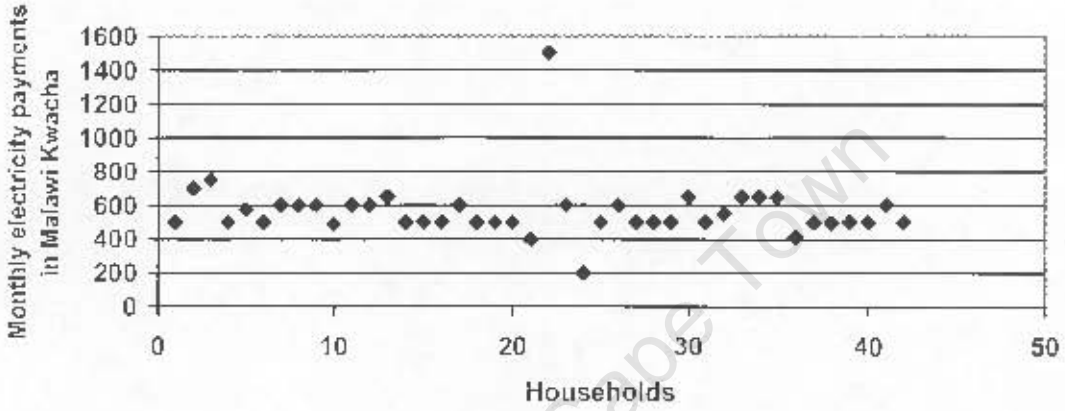


Figure 13: Actual monthly electricity payments in sampled households in 2003

The differences in amounts paid for electricity may be attributed to misunderstandings about the tariff level, which may have come about after the tariff was raised, and due to inconsistent bills which may have caused some households to misinterpret their bills. Another reason for different payments may be the varying income levels and different competing demands placed on different households due to factors such as household size.

Assessing the monthly electricity payments on per capita basis showed that households with fewer occupants tended to pay more than households with more occupants (Figure 14). This may be attributed to the fact that households with more occupants have more competing demands and hence find it harder to pay for electricity compared to households with fewer occupants.

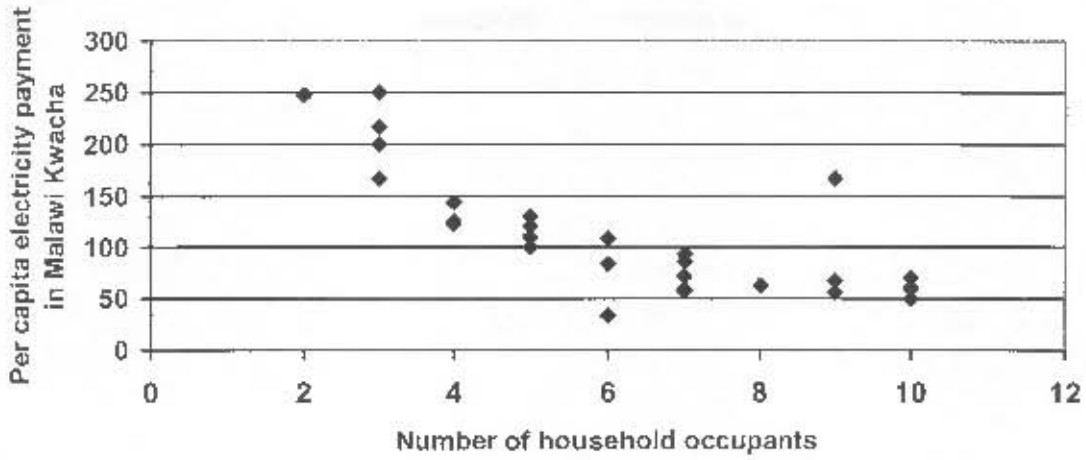


Figure 14: Electricity payments per household per capita

On average, households paid MK 564.76 per month for electricity, which is 3% more than the prevailing tariff at the time of the study. It is interesting to note that the households did not negotiate with ESCOM to pay higher or lower tariffs per month. However, the practice of paying less than the actual bill is prevalent in Malawi even in households with conventional connections. The differences in actual payments of electricity that households make to ESCOM indicate a need for more flexible payment options that allow households to pay-off their debt faster when economic situations improve and to reduce pressures on poorer households, within reasonable limits.

Although the tariff design is a flat rate tariff, and equal among all consumers, an inspection of some of the invoices that consumers receive revealed wide variations, with bills as different as MK550 and MK19, 500. While in some cases this could be attributed to the fact that households had arrears, other households had no arrears and some very high bill could not have been accumulated in the period that electricity has been available in Mbayani even if such households had not paid for electricity, the entire 19 months that they have had electricity. Such enormous bills are attributed to faults with the billing system at ESCOM and are common even among households with conventional electricity connections. Poor billing is causing discontent among consumers (Case study 2), which may have negative implications for the program.

Case Study 2: Electricity bills not understood, sometimes wrong

Jaziel Banda is a married man of 67 years of age. All his 7 children are married and live elsewhere. Occasionally, his pre-teenage grandson visits him for a day or two and that is the only time the radio is played for long periods of time. The Banda household stopped using their hot plate some months before the survey because it got damaged. Their house has 6 bulbs, including two fluorescent bulbs; one of which is located in the lounge and another on the porch, which is switched on all night for security purposes. Apart from subsistence farming, Mr Banda and his wife sell water to earn a living and depend on Mr Banda's pension proceeds as a retired teacher. He gets about MK2, 000 per month from his pension scheme and is overwhelmed by the bills he gets;

> Include in your report that we get strange bills, which ESCOM does not explain. Sometimes we get a bill as high as MK13, 000. Even those with normal connections and with stoves don't use that much electricity. It is as if I am running a boarding school. Although I have never paid more than MK1, 000, these bills make me panic that one day ESCOM will cut my electricity off. May be I should have the electricity removed.

Mr Banda is not alone in his predicament. A number of residents complained about this phenomenon. In addition, Mr Banda, like most other respondents in Mbayani, want his bills to clearly separate the payments for the compact ready board from the payments for electricity consumption so that he can know when he has completed paying for the compact ready board unit.

Case study 2 illustrates the frustrations that customers in Mbayani experience due to poor billing. It also points out to the lack of dialogue between ESCOM and its new consumers. It is interesting to note that while the low cost electrification consumers are not informed of changes in tariffs well before their bills are sent to them, conventional customers are normally informed of changes through the press releases in the media before the change is effected. This calls for the need for ESCOM to improve their service delivery especially with respect to billing and to treat low cost electrification customers in the same manner as conventional consumers where information channels and dialogue are concerned.

Terms of payment and budget control

Up to 92% of the sampled households reported that electricity gave them better control of their household budget as compared to the expenditure strategies used to buy traditional fuels. Respondents reported that this was because they are aware of the expected bill throughout the month which enables them to save for the expenses whilst when using traditional fuels, they often buy different amounts as need arises and depending on their financial status at a particular

time. In addition, prices of charcoal and firewood can fluctuate due to seasons or when the police enhance patrols on illegal charcoal. The budget control benefit is further enhanced by the fact that, disregarding blackouts, the respondents are assured of supply even when they do not have money within the month as articulated by one respondent;

> The good thing about this electricity is that in the middle of the month when you don't have any money you still cook and light up your house. With paraffin and charcoal, if you don't have money before the month-end you go begging and sleep early to save the paraffin so that you don't beg again tomorrow. Now we are at ease through out the month. We just save a little through out the month.

Comparing the flat rate tariff used in Mbayani to the consumption reflective tariff used in conventional metered electricity, 41% of the respondents felt that the fixed rate tariff design gave them better energy budget control because they know what they will pay well in advance while 13% of the households were not sure whether the flat rate tariff design or the consumption reflective tariff design would give them better control over their household energy budget. Up to 46% felt that the metered electricity, which reflects actual consumption, would give them better control over their budget compared to the fixed rate tariff. Respondents mostly attributed the preference for metered electricity to the poor supply;

> As to which tariffs are better, I feel this electricity is expensive but as you know the poor do not have much choice. I do not pay because it is easy but because I see the value of electricity to the wellbeing of my family. But electricity supply is unreliable especially during the rainy season. I feel cheated because we still pay the same price as if we were using it all the time. I know people who now default because the electricity is very unreliable. With this tariff, if there is a black out, they are still charging us. Those on conventional meters have no reading when there is a black out, so they don't pay for that period. Some say its cheaper on conventional meters others say it is expensive. If we knew the truth, may be we would change. For now, because I appreciate the value, I simply pay.

Some households also preferred metered electricity because they have fewer appliances, implying lower consumption than other households within the program that have more appliances [implying higher consumption levels] but pay the same price. In addition, certain households preferred conventional metered electricity because higher capacities would allow them to undertake a wider range of activities such as welding. The results here are also affected by limited knowledge on the costs of electricity and tariff design among users and the lack of experience with other tariff designs.

3.2.5 Fuel usage before and after electrification in Mbayani

The ability of households to benefit from electricity is partly hinged on households' ability to switch from traditional fuels to electricity. The following section examines fuel change patterns that have occurred since electrification so as to understand the barriers that household face in the transition from traditional fuels to electricity once their homes are electrified. The major

applications that the section examines are cooking, water heating, ironing, lighting, media applications and space conditioning.

Cooking

The main fuel used for cooking before electrification was charcoal, which was used by at least 96% of the households including those who used it in combination with other fuels. A total of 66% of the sampled households used charcoal exclusively for cooking before electrification in Mbayani. Up to 28% of the sampled households used a combination of firewood and charcoal for cooking while 4% of the households used firewood only. Only 2% used firewood in combination with charcoal for cooking (Figure 15).

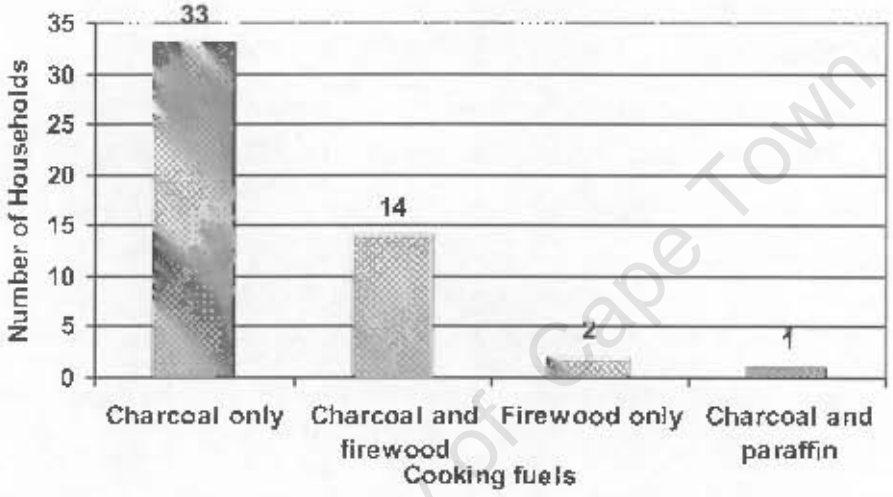


Figure 15 : Fuel use for cooking in Mbayani before electrification

The main source of fuel for cooking after electrification was electricity, which was used by at least 68% of the households, including those who used it in combination with other fuels. Up to 58% of the sampled population switched to cooking with electricity exclusively after electrification (Figure 16), except when there were black outs, in which case they use either charcoal or firewood. Most of these households use one plate cookers, locally known as coils[4] . Up to 8% of the population use a combination of electricity and charcoal whilst 2% use a combination of charcoal, firewood and electricity. Another 30% still use charcoal exclusively as their cooking fuel (Figure 16) while 2% use firewood exclusively for cooking.

[4]Coils are named after the fact that these are the spiralled element of a hotplate and have no supporting frame. They are mounted on a stone, brazier or crude wire frame and have no thermostat

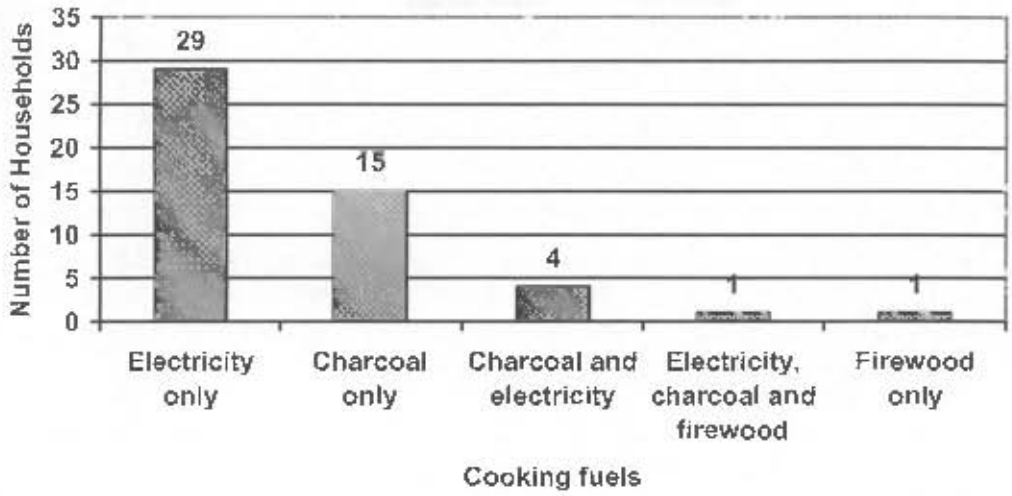


Figure 16: Fuels used for cooking in sampled households after electrification

Households that continue to use charcoal and firewood for cooking mainly attributed the high costs of hotplates as a barrier to shifting to electricity use for cooking. Use of electricity in combination with traditional fuels was mainly attributed to low performance and unreliable cooking appliances and poor supply reliability.

Fuel for bath water heating

None of the households in Mbayani had geysers, a fact that is common in Malawi even in medium income households. Bath water is normally heated in large, custom-made vessels or pots and in some cases, specifically in electrified medium income households an electric kettle is used. The survey observed that fuel needs and strategies for bath water heating in Mbayani, are considered differently from the fuel needs and strategies for cooking foods. The questionnaire was therefore designed to reflect and capture this.

The survey showed that the main fuel for water heating before electrification was charcoal, which was used for heating bath water in 88% of the households. Of the households that used charcoal for heating bath water, 82% used charcoal exclusively (Figure 17) while 6% used charcoal in combination with firewood to heat bath water. Up to 8% of the households used firewood exclusively for bath water heating before electrification. A total of 4% of the households used cold water for bathing. After electrification, electricity was the dominant fuel for heating bath water. Up to 48% of the sample population used electricity to heat bath water (Figure 17), while 2% used electricity in combination with charcoal and another 2% used electricity in combination with firewood. Up to 46% of the valid sample population used charcoal for bath water heating after electrification and another 2% used a combination of charcoal and firewood to heat bath water after electrification.

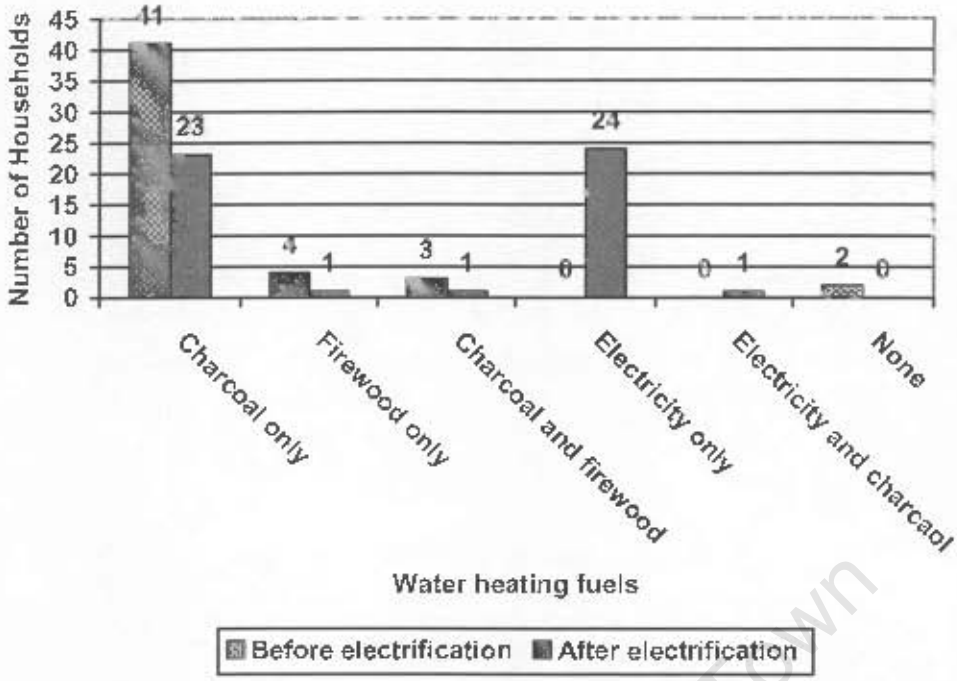


Figure 17: Fuel used for water heating before and after electrification

It should however be noted that bath water heating strategies vary depending on the season, with the number of households using cold bath water decreasing in winter and increasing in summer due to temperature variations.

The use of cold water for bathing may also be a fuel saving strategy in poorer households. This may explain why after electrification, none of the households reported using cold water for bathing since heating water using electricity would not have an additive effect to the electricity bill while using charcoal or fuel for heating water would increase the energy bill. The fact that after electrification none of the households use a combination of firewood and charcoal to heat bath water may be because of the high costs of these fuels, which would make their combination the most expensive option.

Some households attributed the continued use of charcoal or firewood to heat bath water after electrification to the fact that they use coils, which are too fragile to hold big water vessels.

Ironing

Charcoal was the fuel of choice for ironing before electrification and 94% of the households interviewed used charcoal for ironing while the remaining 6% did not have any irons. After electrification, a total of 46% of the households interviewed used electric irons while 42% used charcoal for ironing. Up to 6% of the interviewed households did not possess any irons and either borrow irons or do not iron their clothes at all. To cope with lack of irons, the clothes are

not wringed after washing and once they dry, the clothes are hanged or folded and put under pillows, mattresses or sleeping mats to straighten them.

Households attributed the continued use of charcoal for ironing inability to afford electrical irons.

Fuel for lighting

The main fuel for lighting before electrification was paraffin and a total 96% of the households used paraffin as part of their fuel supply for lighting. Up to 50% of the valid households interviewed used paraffin exclusively (Figure 18) for lighting before electrification while 44% used a combination of paraffin and candles, with a preference for paraffin rather than candles.

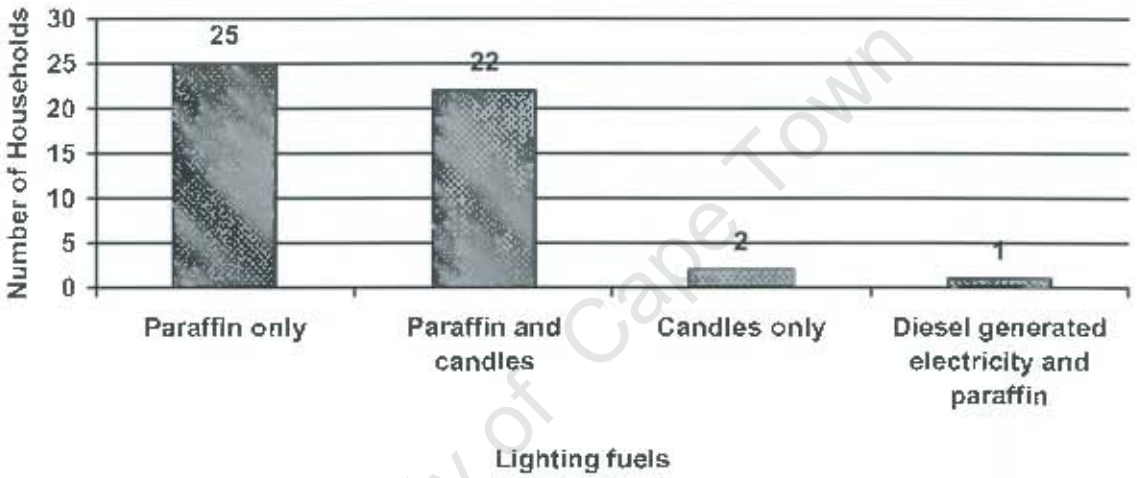


Figure 18: Fuels used for lighting in sampled households before electrification

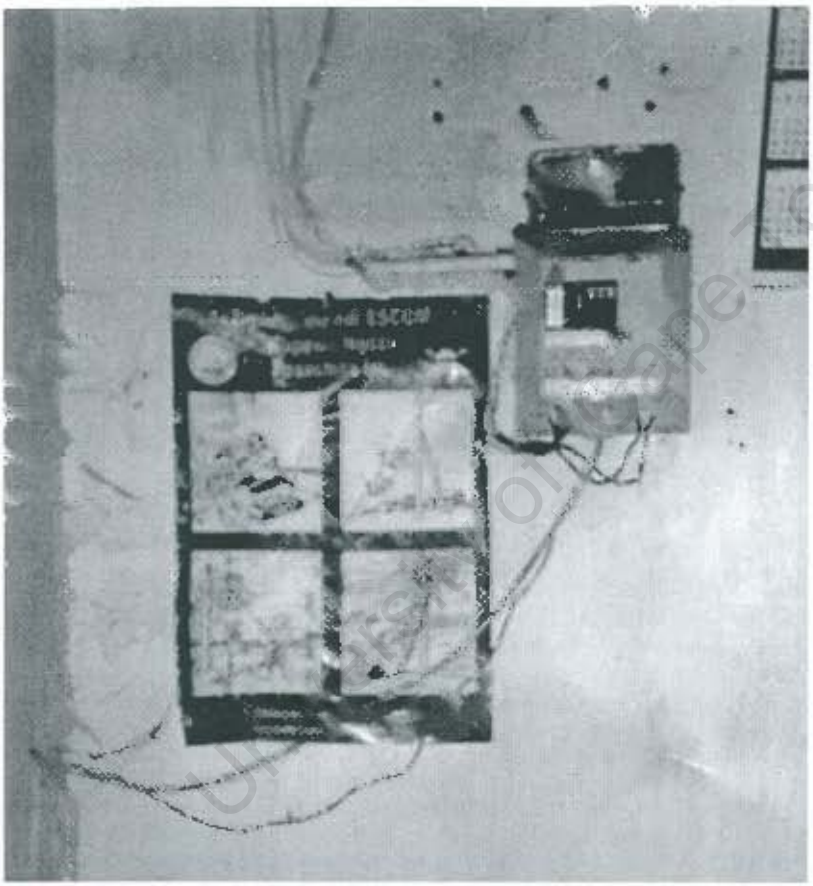
A total of 4% of the sampled population used candles exclusively whilst one household used a diesel generator, in combination with paraffin lamps for lighting purposes before electrification (Figure 18). The lower usage of diesel generated electricity and candles are attributed to their higher costs compared to paraffin lamps and paraffin.

After electrification, all sampled households switched to using electricity for lighting. All households except one were using more than the bulb supplied with the compact ready board. Only one household, with a two-roomed house had not extended lighting and sometimes depended on paraffin lamps for lighting the other room or depended on the light from the bulb supplied with the compact ready board unit which they said was inadequate.

Lighting was by far the biggest change in fuel use, as illustrated by the fact that every household has switched to electrical lighting. This is attributed to the fact that bulbs, which cost between MK10 and MK40, are one of the cheapest electrical appliance and therefore the one

appliance that households can readily afford once their homes are electrified and also every household has a bulb, which is attached to the compact ready board.

However, the compact ready board is often installed in the dining area or the kitchen, leaving other rooms without electricity. Since there is no wiring, households then extend lights to other rooms using extension cords and adapter sockets. This is often done by unqualified or uncertified electricians who are more affordable and available than professional electricians and presents a danger to electricity users in Mbayani. In several households, enumerators noticed that insulated wires were directly "plugged" into the socket without a plug and a fuse (Picture 2).



Picture 2: A compact ready board with some of wires inserted directly into sockets

This may cause sparking, which can result in electrical fires or short-circuiting. Although during the field research the enumerators did not encounter reports of electrical accidents that had occurred under the program, in one household, a respondent complained that the household buys an electric bulb almost everyday because the bulbs burns out almost daily; an incident that happened during the interview. This problem was putting a strain on her finances and the respondent was considering having the electricity disconnected;

> I had this electricity connection so that my children could study under a better light. When the bulb works, it is very helpful because instead of them helping me with the fire at 5 o'clock in the morning, they can study. Or they can study late into the night. But now I have to buy a bulb everyday and that is very expensive so I have decided that once my son writes his exams this year, I will have the electricity disconnected.

Incidentally her neighbours buy the same well-known brand of bulbs from the same kiosk but none of them experience this problem. This problem may then be attributed to faulty wiring in this household. The methods of extending electrical lights to other rooms in the electrified households signify the need to reconsider wiring techniques in houses that are electrified using compact ready boards.

Entertainment and media applications

The main source of power for radios before electrification was dry cells and 74% of the sampled households used dry cells to power radios before electrification while 26% used car batteries to power their radios (Figure 19). In one household, diesel generated electricity was alternatively used with a car battery to power a radio and a television set. Up to 92% of the population did not have television sets before electrification. The three households that had television sets used car batteries to power their television sets. One household alternated the use of car batteries and diesel generated electricity to power its television set before electrification.

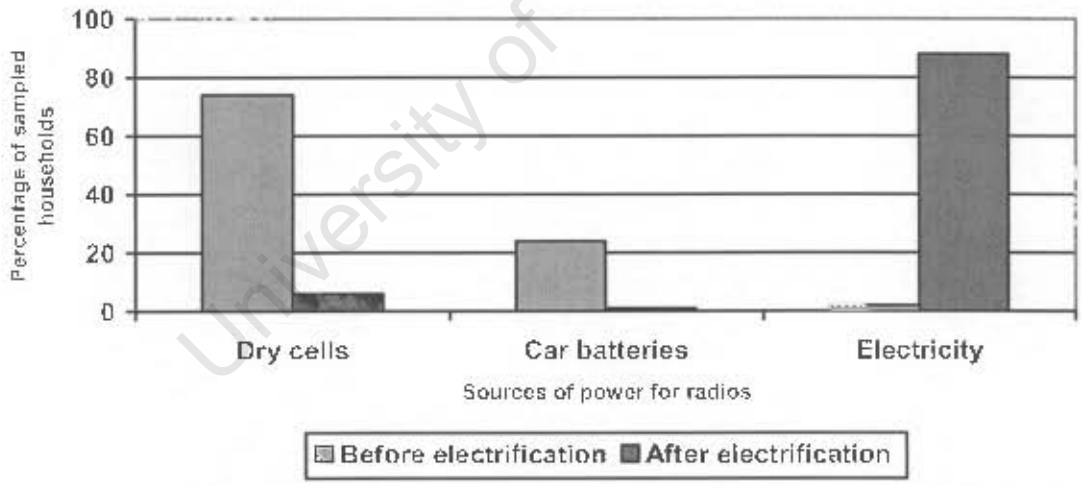


Figure 19: Sources of power for radios before and after electrification in sampled households

After electrification, up to 88% of the sampled households switched to electricity to power their radios, while 6% still used dry cells and one household used a car battery to power a radio after electrification.

The relatively high shift to electricity for powering radios is partly because most households had battery-operated radios before electrification and adapted these to mains electricity once their homes were electrified. One reason for not using electricity to power radios in some of the

electrified households may be because the radios are not adaptable to electricity. Other respondents reported that they were afraid that using electricity to power their radios would damage the radios.

After electrification, 16% of the interviewed households had television sets and all of these households used electricity to power their television sets. It is interesting to note that the number of households with television sets rose by over 100% from the number of television sets owned by the sample households before electrification. This may be an indication that lack of electricity hinders households from obtaining certain household equipment although they may be able to afford such equipment. Two households reported that their television sets had been stolen. This is not surprising because in most urban households putting a television antenna out on the roof often makes the household a target for robbers. Obtaining electricity may therefore have the undesired effect of making some electrified households vulnerable to robbers who hope to steal electrical equipment.

Refrigeration and space conditioning

Up to 96% of the respondents did not have refrigerators before electrification. The two households that had refrigerators before electrification used paraffin to power them. After electrification, 6% of the households had refrigerators and all of them used electricity to power them.

Space conditioning in this context refers to household space cooling and space heating applications. Before electrification, none of the respondents had any form of mechanised house cooling and depended on opening windows or staying outdoors for as long as possible in hot weather. After electrification, 20% of the sampled households acquired fans and all of these households used electricity to power their fans for space cooling.

For space heating, 58% of sampled households interviewed used charcoal before electrification while 42% did not heat their houses when it was cold. None of the households used paraffin heaters or firewood for space heating and in most cases, charcoal for space heating is used in conjunction with other primary uses such as cooking or water heating as a fuel saving strategy.

The sample survey found that although three households had obtained heaters after electrification, only one household used a heater for space heating. The two other households said they had not used their heater because 'it was never cold enough to use a heater'. Up to 88% said that they do not use any fuel specifically for house heating but sometimes benefit from residual heat when cooking on a cold day. Only 4% of the households reported that they used the [ceramic] *Mbaula* for heating their homes in cold weather. One reason for the low

levels of space heating after electrification could be that the survey was carried out in February when the weather is mild, while Malawi's winter is between May and July.

The introduction of low cost electricity in the newly electrified households in Mbayani has resulted in changes in fuel choices and strategies. Major benefits have included discontinued use of paraffin as a lighting fuel except for emergency purposes and for igniting cooking fires. There has also been a substantial decrease in use of dry cells and car batteries for media applications and some decrease in the use of charcoal and firewood for cooking. These changes have spill over benefits such as availability of better quality light, reduced indoor air pollution, reduced fire hazards, cash savings and reduced hardship in preparation of fires. Despite the changes that have occurred, certain households continue to use the fuels used before electrification and other households use both electricity and charcoal for cooking for different reasons (Case Study 3).

Case study 3 echoes strategies used by a number of households in Mbayani, illustrating that use of traditional fuels in combination with electricity is a strategy for coping with unreliable electricity supply and for coping with poor quality appliances. Low quality appliances are also a disadvantage to the utility because they are often inefficient. ESCOM estimates that cooking on a one plate hotplate without a thermostat, as is the case with *coils,* results in average consumption of 188 kWh per month, costing MK564 when calculated at the average tariff of MK3.20 per kWh whilst using a proper hotplate with a thermostat results in an average consumption of 122 kWh per month at a cost of MK366 per month (ESCOM, 2003).

Charcoal and firewood are sometimes also preferred because they serve multiple functions of simultaneous water heating, cooking and space heating where households lack the necessary appliances such as heaters.

Case Study 3: Using multiple fuels as a coping mechanism

Mrs Ambokile is a mother of three and fosters a niece and a nephew. Her husband works as a shop assistant. Although he does not disclose his salary, Mrs Ambokile is sure that he earns less than MK3, 000. Like most residents in their neighbourhood, the Ambokile household own the mud house they live in and so they do not pay rent. Mr Ambokile walks to his place of employment in town and all their children attend a government primary school, for which they pay a school fund of MK8 per term per child. Mrs Ambokile sells charcoal, which she buys in bulk quantities of 50kg to 90kg from a door-to-door salesman. She then repacks the charcoal into smaller bags, which she sells to her neighbours at MK10 per pack. Each pack weighs between 1.5kg and 2.5kg. To cope with unreliable electricity supply and a poor quality electrical "coil", which often malfunctions, Mrs Ambokile uses some of the charcoal from her business for home use. She often uses charcoal to cook foods that take longer to cook such as beans because she is afraid that 'using the coil for long periods of time will cause it to over heat and will damage it'.

Although she now has electricity, she often heats water on the her "*Mbaula*" in winter because this serves two purposes simultaneously; water heating and space heating, since they cannot afford a heater and the coil is too small to provide adequate space heating. Mrs Ambokile feels that making a fire for space heating alone would be a waste of charcoal.

Mrs Ambokile says she is still not sure whether the electricity has made their overall expenditure higher or lower but has developed strategies to deal with the household energy problems that she faces;

> Being poor, we buy cheap *coils*, which get damaged very easily, which means apart from paying for the electricity, we have to buy charcoal and also pay for repairs of the *coil* frequently. Mostly we simply throw the *coil* away and buy another one but now I use the *coil* only when I am not cooking lot of food and use charcoal when cooking *Nsima* because they say stirring vigorously damages the *coil*. The benefits of the electricity have been more in terms of status and lights rather than in terms of saved money. Now they can say Edward's mother has a house with lights. Some of our appliances get damaged because the frequent blackouts and sometimes there is "dim" [brownout or inadequate power].

The survey also noted that charcoal and firewood have an important role in family and social interactions and are sometimes favoured due to traditional tastes as expressed by one female respondent;

> Sometimes you use charcoal because you are used to gathering around the fire and chatting with your family asking your children about school and other things. And most people agree that food cooked on charcoal tastes better than food cooked on hotplates. Especially beans, which you can cook in an earthen pot on the traditional fire but on the hotplate, you use metal pots and the beans taste of metal. You do not get the nice flavour.

The use of traditional fuels for reasons of social interaction and preferred tastes however does not imply preference of traditional fuels over electricity but rather express social and cultural

roles of traditional fuels in Malawi, which have evolved over time with prolonged use of these fuels.

3.2.6 Appliance ownership and usage

The demand for electricity is for the related services it provides and so the benefits of electrification are linked to the users' ability to acquire and use appliances that convert the electricity to the desired forms of energy such as heat and mechanical power for the desired services such as cooking and driving motors in electrical equipment. Households' ability to acquire and use of electrical appliances therefore contribute to the benefits that these households obtain from electricity. The following section discusses findings on appliance acquisition and distribution patterns among electrified households in Mbayani. It is aimed at assessing how appliance penetration has occurred in Mbayani since electrification and exploring the factors affecting acquisition of electrical appliances.

Appliance penetration in Mbayani

Whilst for most households, this is the first time they have had electrical appliances such as hotplates or coils and electrical irons, in most of the cases, they previously owned radios and have converted them from the direct current (DC) mode used by dry cells and car batteries to the alternating current (AC) mode used by mains electricity. Few households have experienced the appliance substitution effect and have since replaced small battery operated radios with bigger radios or high fidelity audio equipment (Hi-Fi). The most common electrical appliances in Mbayani are bulbs followed by radios, most of which were acquired before electrification. The third most common appliances in Mbayani are hotplates and *coils* and the fourth most common appliances are irons (Figure 20).

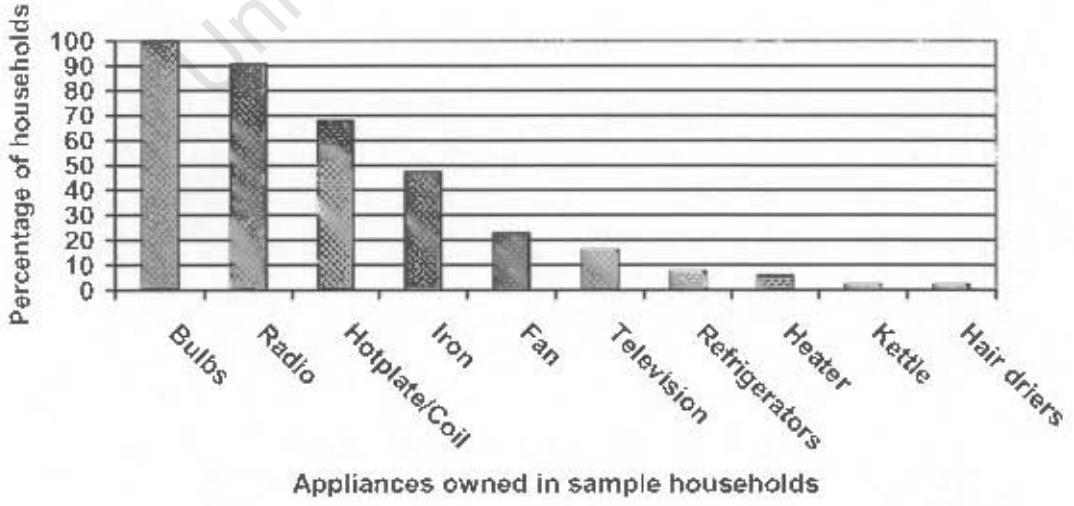


Figure 20: Appliance penetration after electrification in Mbayani

Appliances such as fans, television sets, refrigerators, heaters, kettles and hair driers have had the lowest ownership levels. This may be attributed to their high costs as well as the value that households attach to the services that the households derive from these appliances. The study also found that ownership of an electrical appliance in an electrified household does not necessarily mean that the appliance is being used. For example, three respondents reported that they used batteries for the radios or traditional fuels for cooking for fear of damaging their electrical appliances. This signified that appliance quality and electricity supply quality are barriers to electrical appliance use. In another household, a female respondent said she used the old radio that was battery powered because she was afraid she would damage the new radio, which was powered by mains electricity. However, her husband and sons use the electricity-powered radio, stipulating that gender and power relations in a household may be another factor that determines appliance usage.

Of the three households that had heaters, only one had used their heater. The other two reported that 'it had not been cold enough to use a heater' ever since they bought their heaters.

The survey found that, excluding bulbs, the least number of electrical appliances owned by a household is zero (except for the bulb supplied with the compact ready board unit), while the maximum number of appliances owned by one household was 6 (Figure 21). Excluding bulbs, the average number of electrical appliances owned per household was two appliances and these were usually a radio and a hot plate or coil.

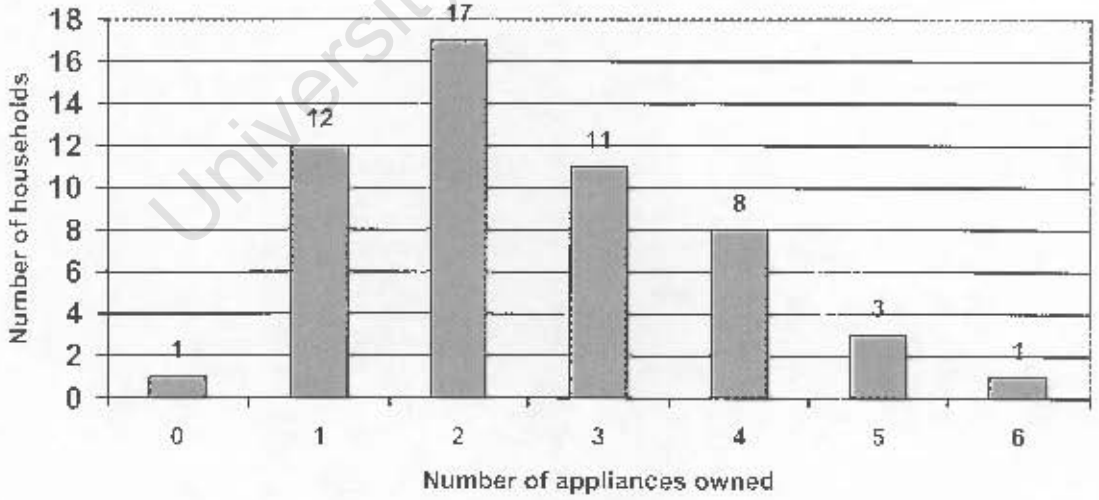


Figure 21: Appliance distribution in Mbayani

The fact that most households cannot afford good quality electrical appliances forces them to buy second hand appliances found in township markets. These are often high-risk appliances and are susceptible to malfunctioning. In some cases, these appliances have to be repaired or

replaced so frequently that possessing them becomes a burden and too expensive for the households. In such a case, households often switch back to using low quality fuels or using a range of fuels such as a combination of charcoal and electricity for cooking, which contributes to an increase in the households' energy burden. In certain cases, where electricity is used in combination with other traditional fuels, having electricity becomes more expensive than relying on traditional fuels alone. This is especially true in the case of Mbayani because the tariff paid is a flat rate tariff, such that using other fuels in addition to electricity significantly increases the energy bill, without decreasing the electricity bill itself. In contrast, in cases where the bill varies with usage, households without certain electrical appliances would have lower consumption, reflected in lower electricity bills than households that use more appliances.

Appliance ownership and income levels

Assessing the relationship between the number of appliances owned by a household and the income levels of the household showed that there is limited correlation between the number of appliances owned and the income level of the household (Figure 22). It should however be noted that Figure 22 excludes the bulb supplied with the ready board unit since this was part of the package and did not require extra expenses on the part of the household.

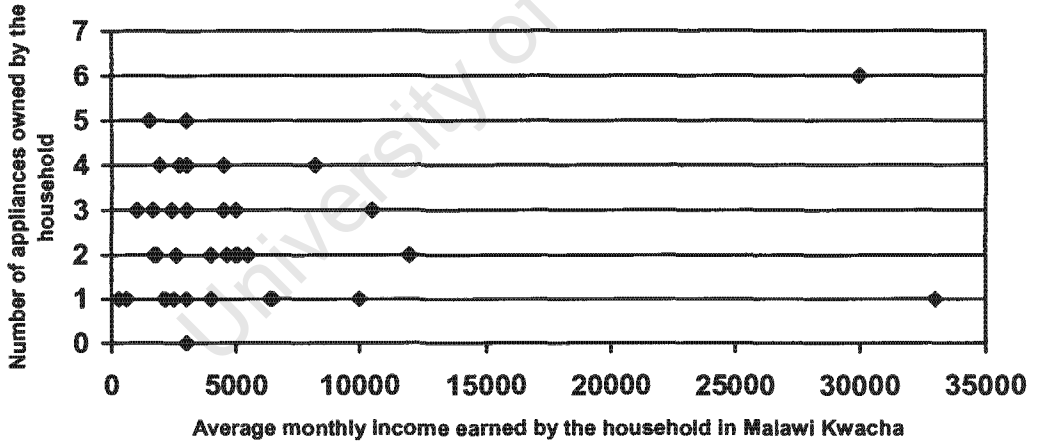


Figure 22: Appliances ownership and household income levels in Mbayani

The lack of direct correlation between household income levels and appliance ownership suggests that deciding on purchasing electrical appliances in a household is a complex decision for poor households, which not only involves incomes but also a number of social, technical and economic factors. The relationship between men and women within the household, especially spouses, is one of the contributing factors to the number and type of appliances

accumulated by a household after electrification as articulated by one of the female respondents;

> Some women have a voice and tell their husbands what appliances to buy and obviously they will insist on a hotplate, but if you leave it to the men they will buy a big radio and cassettes all the time.

Another reason for the limited correlation could be that spouses in poor households may have similar income levels and may therefore have more balance in decision making compared to households with higher income levels where earning powers are usually highly skewed in favour of males. In addition, poor households with higher income levels are sometimes responsible for more extended family members and sometimes have more competing demands for their incomes and lower per capita incomes than poor households with lower incomes. This calls for more research into effects of introduction of electricity on the intra-household as well as inter-household resource allocation and power relations. This would help policy makers understand how to provide electricity services without compounding imbalances in resource allocation.

3.2.7 Effect of Electrification on SMEs in Mbayani

The versatility of electricity enables a number of productive activities to be carried out that may not be easily done with use of traditional fuels. Such activities may include income generating activities such as cooling drinks for sale and trading for longer hours. The ability of households to improve their financial situation as a direct result of electrification is crucial because it can lead to increased incomes, which can ease households' ability to pay for the electricity service as well as improve households' general wellbeing. The following section discusses the effect that the low cost electrification program in Mbayani has had on the SME sector in Mbayani.

Contribution of electrification to the SME sector in Mbayani

Contribution of electrification to the SME sector was considered at three levels namely; emergence of new business ventures as a direct result of electrification, increased business transactions in existing and new businesses and value addition to existing products and services due to the availability of electricity. The gains or losses of incomes in businesses that may have resulted from changes in energy related expenditures as a result of electrification were not examined because of the lack of clarity and demarcation in input expenses in most SMEs in Malawi and Mbayani in particular.

About 90% of sampled households had an SME, and all of these SMEs can be classified as micro-enterprises. These included houses for rent, food sales, water sales, sale of imported second hand clothes, photography services, barber shops, paraffin and charcoal sales among others. The study found that at least 23% of the sampled households had kiosks, which ranged

from shacks that sell few or specialised products, locally known as '*Okala*' to grocery shops that have wider range of stock and are usually well built. At least 50% of these kiosks could be classified as grocery shops.

At the time of the study, only two of the newly electrified households in Mbayani had started new ventures as a direct result of the introduction of electricity in their homes. A female respondent carried out one of the new ventures. She used electric light to enable feeding of day old chicks, which she sells in the neighbourhood. Another new venture that started as a direct result of acquiring electricity in a household was fixing of radios including soldering, testing and extending working hours. This is done by a male respondent, who fixes radios to supplement his monthly income as a sales assistant.

Benefits that existing SMEs experience that are directly linked to electrification of households include the ability to work at night and extended trading hours. In one case, the ability to iron second hand clothes enabled the business owner to charge higher prices than un-ironed clothes because ironed clothes are hung in a shade, while un-ironed clothes are heaped and the customer has to sift through the pile. Hanged clothes then fetch higher prices than piled, un-ironed clothes. Four of the six grocery shop owners, reported a diversification in the range of products sold, to include dairy products, drinks and other perishable food products. The shops are also able to offer music, which attracts more customers than before. Two grocery shop owners reported that they now open their shops for longer hours than before since they use electricity for lighting their business premises after dark (Table 11) and that the trading environment is now safer after dark because of better lighting. All the kiosks that experienced these benefits are attached to the electrified houses and so lights were extended from the houses to the kiosks.

Business	*Contribution made due to electricity availability*
Groundnut Snacks	• Roasted and packed the night before sales
Other Snacks	• Cooked using electricity
Fixing Radios	• Soldering done using electricity • Other work done at night (extended working time)
Charcoal	• Re-packaging done at night (extended working times)
Kiosks	• Extended trading hours and increased sales • Able to offer music, cold drinks and perishable foods such as milk
Second hand Clothes	• Ironed at night • Clothes graded at night • Accounts reconciled at night in better light
Poultry	• One day old chicks able to feed all night

Table 11: Contribution of electricity to income generating activities in Mbayani

The other two grocery shop owners that did not report benefits had grocery shops at the road side and their shops have had conventional electricity well before they got electricity in their homes. It is interesting to note that their shops stock the widest range of products and services in the area, including cold drinks and fresh food products. In addition, one of the shop hosts a welder on the veranda, who pays the shop owner for use of electricity.

Although the survey does not quantify the contribution of electrification to SMEs in terms of actual increases in incomes or savings by SMEs due to use of electricity, the extension of working, including preparatory and trading hours, value addition and the emergence of the two new ventures that depend on electricity suggest that electricity has benefits on the SME sector in Mbayani. The sense of a more secure trading environment may also encourage development of new SMEs, introduction of new services and increases in the range of products sold in the area. These benefits may have spill-over effects of increased incomes and employment.

The low level of new ventures in the area can be attributed to the short time in which electricity has been available in the area. In the other SMEs, which had been in existence before electrification, electricity had resulted in the diversification of goods and services and extension of trading hours, which may imply increased profitability and so increased incomes for the involved households. However this was true mostly for home-based businesses including kiosks that are attached to houses, since the electrification program was restricted to houses. There may also have been a decrease in cost of inputs compared to the time before electrification, when business owners used paraffin to light up their shops (or extend working hours) and battery operated radios for entertainment, both of which are more costly than using electricity.

Other factors that may have contributed to the low levels of new SMEs resulting from electricity connections include the following;

- ESCOM instructed households to refrain from using the electricity for business ventures. This may have caused some households to refrain from undertaking business ventures that use electricity while others may not have reported their business ventures during the survey because of fear.
- Economic hardships being experienced throughout the country, which means aspiring entrepreneurs may not be able to save enough money to embark on new SMEs and buyers spend more cautiously due to competing demands.
- Supply capacity limitations of electricity, which excludes businesses that require higher capacities such as welding even if they are home-based.

In addition, a number of crosscutting issues, such lack of social infrastructure and limited availability of credit facilities may hinder households from embarking or expanding their SMEs (Case study 4).

Case Study 4: Its not just electricity

Tamara Msosa is a mother of five and her husband Weston works as a shop assistant in the city centre. His salary is about MK2, 000 per month but due to financial pressures at home he often gets his pay in smaller advance packages of his salary throughout the month and so at the end of the month he usually has a debt that is carried over into the next month. The Msosa family also fosters two orphaned children. When they got electricity, their lives changed, but not necessarily for the better according to Tamara;

> We are grateful for this form of electricity. It is something we could never have afforded otherwise. But development is not just electricity. My children can now read under better lighting but then the education system is very bad. So what is their future when their teachers don't come to work because they are busy alleviating their own poverty? They have the electricity but now there is nothing for them to read. All of us cannot afford private schools. Can you see a future for my children? We live in the city but still get water from the dirty river down there.

Tamara feels that the benefits of the electrification program are undermined by the increasing costs of living and feels that development of small businesses in the area would be crucial in maximising benefits of any pro-poor program.

> Five years ago, my husband used to get less than MK1, 000 but we bought more than we buy now with MK2, 000. I have tried some businesses but they are too small and every one is doing the same business so there is no one to buy from you. These snack businesses never bring a profit. It is just a way of saving money since you cannot go to the bank with so little and you may need it when the bank is closed. The government has to help us get more than electricity because these programs will not work if people cannot make some money.

Mrs Msosa cited the lack of capital and authentic business co-operatives or groups as a barrier to SME development that the poor, especially women face;

> We are poor and don't have capital so we need business loans. To get a loan we have to join business groups but most of these women's business groups are either not authentic or have difficult rules so our husbands don't want us to join because you end up with more debt and can loose everything you had before joining the group and the banks lend to the rich only. Where can a person like me get a security to get a loan for a fridge? I want the loan because I have nothing and they want something from me; from where will I get that something for security if am poor? If I had a fridge I would be selling drinks and fizzy pops to schoolchildren.

Case study 4 illustrates that benefits from household electricity are affected by several interacting factors. It illustrates the need for more integrated approaches in electrifying households if electricity is to help alleviate poverty in poor households. In addition, for electrification to benefit SMEs; there will be need for special interventions that specifically target the SME sector in urban areas, which will have to be carried out together with other business development programs such as business skills training and provision of low risk loans.

3.2.8 Users' perception of the low cost electrification program

The next section discusses the benefits and barriers of the low cost electrification program as perceived and ranked by the compact ready board electricity users. The aim of the section is to highlight the benefits and challenges that face the low cost electrification program so as to identify ways of reducing and where possible, eliminating the barriers and enhancing the benefits for both the existing Mbayani program beneficiaries and future low cost electrification program beneficiaries.

Electrification benefits

The respondents ranked the uses of electricity according to what they felt benefited them most. On average, cooking was rated the most important benefit from the electrification program (Table 12). Up to 56.5% rated cooking first most important benefit, whilst 12.5% rated cooking second and 10% rated cooking the third most important benefit. Benefits derived from cooking with electricity included reduced cooking times, cleaner pots and reduced indoor smoke[5]. Respondents ranked information because of increased use of radio as the second most important benefit. Up to 17% rated it first while 25% rated it second in a rank of 1 to 4. Security was rated third most important benefit. A total of 13% rated security as the number one benefit of electrification whilst 17% rated it second. The fourth most important benefit was reading, with up to 9% of the respondent rating it first, while 17% of the respondents rated it second on a rank of 1 to 4(Table 12).

Rank	*Cooking*	*Information through radio*	*Security*	*Reading*
1	56.5%	17%	13%	9%
2	12.5%	25%	17%	17%
3	10.0%	20%	15%	15%
4	5%	14%	5%	10%
Overall Rating	1	2	3	4

Table 12: Benefits of electricity ranked in order of most important benefit derived

Respondents emphasised that the reading (ranked 4) was not necessarily studying by school going children. They specified that reading along with radio use, increased their knowledge of current affairs[6] and that extended studying by school going children was a function of several other factors such as quality of education available to the children.

[5] Interestingly, more men than women stated the benefit of reduced indoor smoke. This is probably because women have been used to indoor smoke and consider it part of their daily lives. Also, culturally, women are not expected to complain about problems related to cooking experiences such as smoke and getting burnt.

[6] It was interesting to note that most respondent pointed out increased political knowledge in particular as an important benefit from electrification. This is probably because Malawi is a relatively new democracy, having had its first democratic elections in 1994 and is to hold its third democratic elections in 2004.

Other benefits in order of their importance as perceived by the respondents were ironing, music for entertainment due to increased radio, water heating, use of refrigerators, entertainment from video and television and fans. Respondents also stated the following benefits;

- Ability to budget effectively for energy expenses.
- Ability to use electricity even when they have no money.
- Reduction in shopping times and distance travelled to buy charcoal, firewood and paraffin.
- Increased usage of electrical appliances.
- Acquisition of new appliances and status in society.
- Increased sense of social inclusion in mainstream development.

The ranking of benefits and the levels of appliance penetration shows that there is a linkage between households' perception of benefits derived from electricity use and how the households prioritise appliances as well as the cost of appliances (Table 13).

Type of electrical appliance	*Appliance penetration rank*	*Related benefits rank*	*Related services*	*Cost ranges in MK*
Bulbs	1	3 and 4	Security and reading	MK10-MK40
Radios	2	2 and 6	Information and entertainment	>MK700
Hotplates or Coils	3	1	Cooking	>MK400
Irons	4	5	Ironing	=>MK700
Fans	5	10	Space cooling	>MK500
Television sets	6	9	Entertainment	>MK10,000
Refrigerators	7	8	Food preservation and cooling drinks	>MK15,000
Heaters	8	Not ranked	Space heating	>MK700
Hair Driers	9	Not ranked	Hair drying	>MK900

Table 13: Appliance penetration, ranked benefits, and estimated costs of appliances

This suggests that once homes have been electrified, households will first buy the cheaper appliances that they feel benefit them most, such as bulbs, radios and hotplates. Radios have the added advantage in that most households had battery-operated radios before electrification, which households adapted to electrical power, once their homes were electrified. Over time, or in homes with higher incomes, households then prioritise the next cheapest convenience appliances such as irons. Fans and televisions seem to be luxury appliances that are bought after convenience appliances. While refrigerators are highly valued in most households, their high costs often means that households forego refrigerators, sometimes in favour of more convenience or luxury but cheaper appliances such heaters and hair driers. This pattern seems to be a result of logical decision-making.

Barriers to maximizing benefits of low cost electrification

Although low cost electricity has produced benefits for users in Mbayani, there are barriers that are limiting the positive impact of electricity supply in the newly electrified households.

All respondents cited the high cost of appliances as a major barrier to maximizing benefits from the low cost electricity supply. Households said that they were unable to obtain one or more of the appliances, which they considered essential, such as hotplates, irons and refrigerators, due to the high costs of the electrical appliance(s).

Another problem faced by the users, which they cited as a barrier to benefiting from electricity supply is the quality of supply and the frequent blackouts that the residents experience. Up to 57.5% of the respondents cited frequent blackouts as one of the problems that they face. It should be noted however that blackouts are not specific to Mbayani and unplanned and planned supply interruptions are often experienced by all ESCOM customers.

A total of 32% of the respondents cited high tariff levels as the disadvantage of electricity while 30% of the respondents cited lack of dialogue as a problem that hindered them from fully realising the benefits of electricity. In particular, respondents wanted to be informed about changes in tariffs in advance rather than seeing changes on invoices. Respondents also had new questions on electricity use that have arisen with the experience of using electricity. Poor billing also raised concerns among residents that they will have their electricity disconnected, because people do not understand the high bills that they get. With the recent introduction of surtax charges to consumer goods in Malawi, a number of residents believe that surtaxes are affecting their monthly bills while others believe the inconsistent bills are a result of interest charges on the compact ready board cost. This explains why a number of households have started paying more than the designated MK550 per month. Billing inconsistencies are another reason why respondents felt there should be continued dialogue between the utility and the consumers.

Up to 21% cited limited supply capacity, which limits the range of the uses of the electricity as a barrier to maximising benefits of the electrification. Respondents also felt that limiting electricity connection for household use and not extending it to businesses such as welding and other SMEs, which are popular in the area, significantly reduced the economic benefits that they could have realised from the electricity.

At least 15% of the respondents had stopped using at least one appliance because they were afraid it would be damaged or were not sure if it was within the voltage requirements of the electricity supply capacity. This fear is attributed to the fact that the majority of the residents in Mbayani are using electricity for the first time in their homes and therefore lack the benefit of

experience. The fear is further compounded by malfunctions of low quality appliances that the poor households use as expressed by one woman;

> We have a radio, a hot plate and these lights. I used to use the hotplate but I no longer use it because it causes the switch to fall (cut out). I also don't use the electricity for the radio because I am afraid that it will be damaged, so I keep using the batteries and this is very expensive. I don't want the electricity to damage my appliances so I would rather buy expensive batteries than have the electricity "burn" my radio, which is more expensive to replace.

The fear of damaging appliances is also attributed to poor supply quality. Very few households in Mbayani are aware that their appliances can be replaced by ESCOM if they were damaged by poor supply quality. Even with this knowledge, the long process involved in investigating such cases deters consumers from laying compensation claims for damaged electrical equipment.

About 17% of the sampled households complained that at least one of their electrical appliances malfunctioned or was damaged. This was attributed either to faulty appliances or to voltage fluctuations in the ESCOM system, which has been known to frequently damage equipment even in households outside the program.

The high costs of appliances and poor supply reliability are the two major barriers, hindering households from benefiting more fully from their electricity connection. Each of these was cited by over 50% of the respondents as a barrier.

3.3 Key informant interviews

Key informant interviews were carried out in order to get a community leaders' perspective of the low cost electrification program, in line with the main objectives of the study.

Interviews were conducted with two key informants that are influential in development activities in Mbayani. The first key informant, Mr Gama, is Chairman of the community's development committee in Mbayani. He is also the Chairman of the community's chapter of the ruling party, the United Democratic Front (UDF). In addition, he has a lawn in his backyard, which is used for public meetings in the area. This is important because houses in Mbayani are built very close together and a lawn that is not used as a vegetable or maize garden provides an important meeting place where society forums are held and critical issues discussed. It provides some level of prestige to the owner because it replaces the traditional "*bwalo*" which was the open area that acted as the chief's court and a community centre in the traditional Malawian setting. These are some of the reasons why Mr Gama was chosen as the mediator between ESCOM and the community in Mbayani during the launch phase of the compact ready board

program. Mr Gama convened meetings during the launch phase and continues to act as a mediator between ESCOM and newly electrified households in Mbayani and this is why he was selected as one of the key informants during the survey. In fact, the section of Mbayani where compact ready boards were used is now commonly known as "Gama area" because of the role that Mr Gama continues to play in the program.

The second key informant was Mr Paul who is aged 65 years old and is a village elder in Mbayani. Mr Paul was for a long time the Chairman of the Mbayani branch of the former ruling party and is now a secretary of the Mbayani branch of the current ruling party. He also sits on the community's council of elders. During the launch phase, he was involved in co-ordinating meetings in the section of Mbayani that is far from Mr Gama's residence.

Both Mr Gama and Mr Paul are also beneficiaries of the program and so have first hand experiences with the program.

3.3.1 First key informant interview

According to Mr Gama, at the start of the implementation phase, ESCOM officials including the Marketing Manager, who is the program co-ordinator for the low cost electrification program visited Mbayani to provide the community members with relevant information of the program. The sequences of the visits from ESCOM are outlined below.

- During the first visit, ESCOM officials approached Mr Gama and explained to him that ESCOM wanted to electrify 150 poor households at a cost that was lower than conventional electrification costs by using compact ready boards.
- Two weeks after the first visit, the ESCOM officials visited Mr Gama to show him a compact ready board and explain to him how it works. This was done to enable Mr Gama to brief the residents of Mbayani and convene a public meeting on behalf of ESCOM.
- A week after the second visit to Mr Gama, ESCOM officials and Mr Gama convened a public meeting to launch the program. During the meeting, ESCOM officials introduced the program to the public and answered questions from the community members.

During the launch meeting ESCOM officials explained a number of aspects of the electrification program including the capacity constraints of the electricity, (what it could or could not be used for), the ownership of the compact ready board units, tariffs to be paid and frequency of payment. Potential users were instructed not to use the electricity for income generating activities. The cost of the compact ready board would have to be paid to the utility as part of the monthly electricity tariff and would be recovered over a period of 5 years after which, the ready board unit would belong to the household. ESCOM officials also explained to the community members the dangers of electricity, how to avoid accidents and handed out posters, depicting how electricity accidents can occur and how to avoid them.

Applications for electricity connections were made on application forms, which were made available from Mr Gama's residence. The applicants had to include general directions to their homes to facilitate installations since there are no street addresses in Mbayani. According to Mr Gama, a lot of people wanted to apply for the electricity but since there was a limitation, only 150 households were approved and subsequently connected. Application forms were handed out based on first-come, first-serve basis and approvals were made based on the household's demonstration of the ability to pay for electricity. Mr Gama collected all households' payments for the connections on behalf of ESCOM. One problem that arose from this arrangement was that there were more people who wanted to apply for connection than the allocated number of application forms.

Once the electrification program was complete, the first problem that emerged was that of supply quality and reliability;

> One of the problems that people have with this electricity is its reliability. Initially, there was a problem with the wires [transmission cables]. They used to touch and spark and after reporting this to ESCOM they came to repair them but the problem continued. They later replaced the cables and this problem has stopped. But there are too many black outs and now people want metered electricity because customers on metered electricity don't pay when they are not using electricity but for us, there is a fixed monthly tariff yet sometimes for a month, we only get electricity four to five hours a day. Sometimes we have no electricity for the entire day.

Mr Gama said one other common complaint that residents lodge with him is that of exorbitant bills;

> Initially the people were enthusiastic about the electricity and were willing to pay because no good thing is free. But then ESCOM started sending very high bills and this de-motivated people. People have brought me invoices showing bills like MK13, 000 and MK19, 000 but I tell the people not to worry. I just say that this is a computer error because when residents go and pay MK1, 000 or MK2000 they are reconnected and ESCOM would not reconnect them if they owed them [ESCOM] so much money. I also know that people in Namiwawa [an upmarket suburb in Blantyre] do not pay such high bills. But people are afraid that after getting used to electricity they will be disconnected.

The protocol that people in Mbayani expect from ESCOM is also a point of concern, especially in terms of communication. According to Mr Gama, people feel ESCOM treats poor customers differently from their non-poor customers.

> The people here think ESCOM is rude. The residents complain that when ESCOM wanted to install compact ready boards, they conducted a public meeting, but now they change things without contacting them. This has been very bad and at one point, ESCOM staff disconnected people without warning them and disconnected others that had no arrears. This angered people and they vandalised ESCOM vehicles and the transformer here. They also sent them a letter, threatening to harm their officials if they came to Mbayani. I helped sort out that issue but now we hear we no longer own the compact ready boards and that the tariffs have been increased yet ESCOM officials did not conduct a meeting to tell us about these changes. In addition, people who choose to pay more do not know whether or not they have finished paying for the compact ready board unit. The residents of Mbayani feel that this is because they are poor and most of them are uneducated so ESCOM takes advantage of that.

Despite the problems faced, Mr Gama pointed out that a lot of the residents feel that having electricity with problems it is better than having no electricity at all.

> This electricity has really benefited most people and more people want it. That is why people can put up with some of the problems since cheap things have their own problems. Households that are electrified are saving on the money they used to spend on charcoal and paraffin and electricity is very convenient. Electricity also gives us some status in the community. Before electrification, we felt we were no different from villagers even though we live in the city. Now there is a difference and we can say we live in Blantyre City because we have electricity. I think ESCOM and the government should continue with this program because people are always asking me when the program will start again.

3.3.2 Second key informant interview

Mr Paul has lived in Mbayani for over 30 years and although his home is about 10 minutes walk to the city centre, electricity was something he saw in offices or in homes of "bosses" and he thought he would never see electricity in his home in his lifetime.

> When I came here over 30 years ago, I built and wired my own house but I could not get electricity because it was too expensive. We gave up a long time ago on the idea of ever having electricity so I bought land and planted a tree nursery, which is the forest you now see around us. Now that we have electricity, when we switch on our porch lights, it is bright at night, like a city, not dark like a village. We felt like outcasts in this city. In fact, although we were in the city, in reality, we were in the village. Now with electricity, there is a difference with village life. My wife can make a quick cup of tea for a visitor and our shop can stay open until 7 P.M and although crime is on the increase country wide, having electricity feels more secure.

According to Mr Paul, having electricity with problems is better than having no electricity at all and the people in Mbayani want the project extended to other parts of Mbayani and other townships in the city as well as in villages outside the city limits. He feels that there is a marked improvement in the quality of life once electricity is installed especially for women who inhale less smoke and are less busy.

> My wife can now attend development committee meetings without worrying about fetching charcoal or firewood, and my grandchildren can study. May be if the electricity had come earlier, my own children would have been better educated. Studying in candle light was very hard for them and expensive for us. The biggest problem is that when things change ESCOM does not inform us. Mostly we hear rumours and people start going to ESCOM offices to ask questions and we start getting some answers. That makes people angry and so they sometimes sabotage ESCOM equipment.

Mr Paul says that the main reason why people vandalised equipment and threatened ESCOM employees when ESCOM disconnected electricity supply to their homes was because the households were not told in advance and some were disconnected despite the fact that they were paying their bills. He said ESCOM could easily set up dialogue with residents through community leaders and avoid such incidences.

> The lack of continued dialogue between ESCOM and us customers makes things look worse than they actually are and may be your research can find out from ESCOM why the dialogue is not there. That is why your team initially had problems because some people thought you

> were here to disconnect electricity. We are even surprised that people that are not from ESCOM are interested in how we have benefited from the electricity and the problems we face, whilst ESCOM itself has never come to investigate. I thought you were from an electricity supply company that wanted to compete with ESCOM or an NGO that wanted to help us. As community leaders, we welcome development efforts and ESCOM can use us to help them because in doing so, we help ourselves.

Mr Paul also felt that there might be problems because ESCOM is not extending the services to other households in the area. He feels that the benefits can be enhanced at community level if more people had electricity.

> It is like a family where one child is eating meat and the other vegetables only. That way the family cannot grow well. This program needs to be extended to all households that can pay. In future they must also consider giving us appliances so that we can benefit more. What is the point of having electricity if you cannot cook with it or benefit by using it to get some income? Those that want appliances should be allowed to apply for them on the electricity application form and then they can pay ESCOM back over time. These low quality appliances that we get from the market are very expensive and not reliable. If something goes wrong with the appliance, even the same day you bought it, the sellers refuse to exchange it

The two key informant interviewees articulate most of the perceptions of users that the respondents of the household survey portrayed including the benefits of electrification as being convenience especially for cooking and lighting as well as for elevating the status of the electrified households. The key informants also underscore the role that poor service delivery such as supply quality and billing erode customer good will, leading to reduction in willingness to pay and vandalisation of infrastructure which can be costly for the utility. Breakdown in dialogue and protocol further worsen relations between service providers and consumers while lack of support programs such as provision of electrical appliances limits the benefits that poor households derive from the electrification program.

CHAPTER 4: LESSONS FROM SOUTH AFRICAN ELECTRIFICATION PROGRAM

4. Introduction

This chapter provides a review of low cost urban electrification initiatives in Southern Africa, from which it draws lessons for Malawi.

The discussion on South Africa's electrification program is based on literature review and starts by providing an overview of the South African economy and poverty in comparison to selected Southern African countries. The aim of this overview is to contextualise the South African experience. The chapter proceeds to present a brief on the structure of the South African power sector, aimed at highlighting the differences and similarities that exist between Malawi and South Africa to further put the review in perspective. Finally, the study discusses the general processes of electrification in South Africa and the lessons of these processes on the supply side, including a discussion of a unique case where a public-private partnership was used to electrify poor urban households. The study then proceeds to discuss some impacts of electrification on the demand side. However, because the literature on South Africa had different focus than this study, not all findings from the Mbayani study have directly linked lessons from South Africa.

4.1 Demography, economic development and poverty in South Africa

South Africa occupies an area of 1,219,090 km^2 in the southern most part of Africa. It is situated between latitudes 22° and 35° South and longitudes 17° and 33° East. In 2001, the population of South Africa was estimated at 44.6 million inhabitants (GoSA, 2002:7). Population is estimated to have grown by 2.3% between 1995 and 2000. In 1998, 50% of the South African population lived in urban areas.

South Africa's economy is one of the best performing economies in SADC and Africa in general; with a GDP per capita by power purchase parity of US$ 8,488 in 1998 (SARPN, 2003).This high GDP per capita however masks enormous differences that exist between the rich and the poor as shown by the Gini Coefficient[7]. One poverty and inequality study conducted in 1998 in South Africa showed that the country's Gini coefficient at 0.58, was the second highest in the world, being preceded by the Gini coefficient of Brazil which stood at

[7] The Gini coefficient measures income (or expenditure) inequalities by measuring the extent to which incomes (or consumption expenditure) among individuals or households within an economy deviate from perfectly equal distribution.

0.61 (May, 1998: 1-2). The study also revealed that the poorest 40% of South African households, equivalent to 50% of the population, receive only 11% of total national income, while the richest 10% of South African households, equivalent to7% of the population, receive over 40% of total national income. A comparison of income inequalities in five selected Southern African countries, further illustrates that South Africa's income inequality is higher than some of its poorer neighbours (Figure 23).

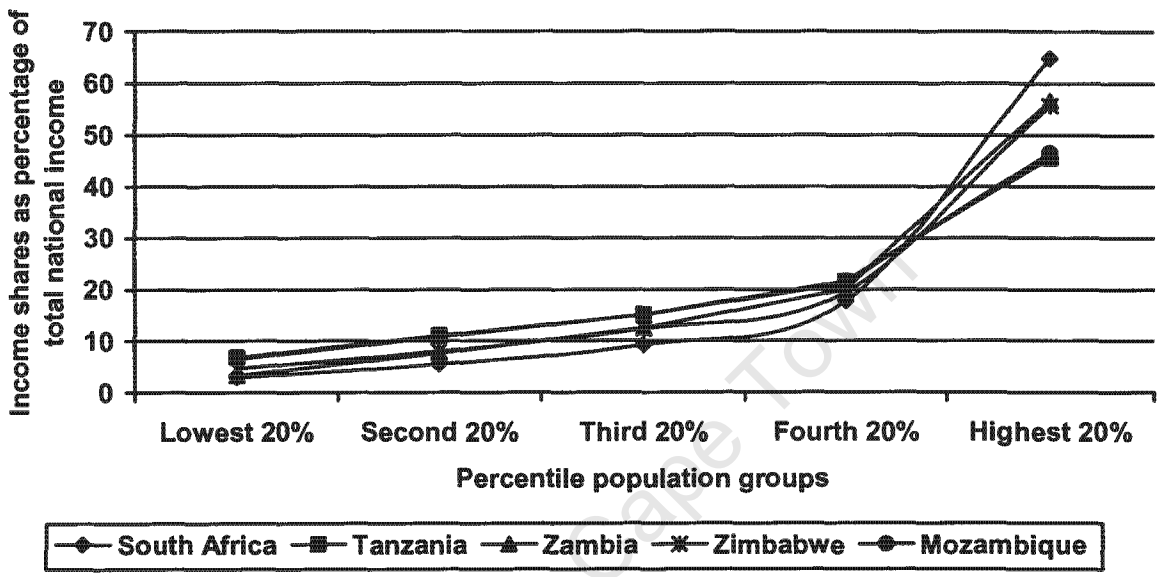


Figure 23: Income inequalities in five selected Southern African countries

Source: Adapted from World Bank, 2002

Notice that, in the lower income ranges between the lowest 20% and the fourth 20% income groups, South African households have the lowest income levels (Figure 23) and then South African income levels are highest in households in the last and highest 20% income group, with a particularly sharp increase in incomes in this last group compared to the other Southern African countries (Figure 23). These inequalities are mostly attributed to the policies of the apartheid era and so the provision of electricity to the poor in South Africa is not only a developmental issue but also a political issue, as part of a broader initiative that seeks to address the disparities resulting from the apartheid era.

4.2 Features of the South African electricity supply industry

The electricity supply industry in South Africa is semi-traditional in that unlike most traditional utilities which undertake all electricity supply functions, Eskom undertakes electricity generation, transmission and distribution but some of the generation and distribution functions, including reticulation are carried out by local authorities (Figure 24).

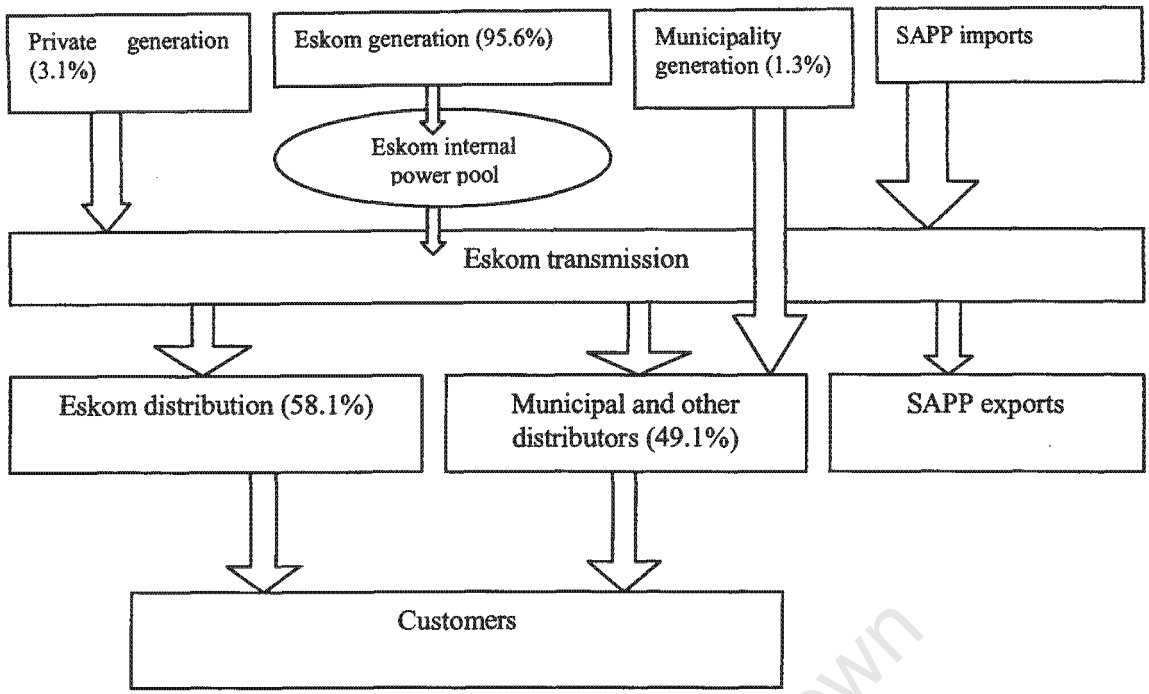


Figure 24: The structure of the electricity supply industry in South Africa
Source: Adapted from Eberhard, 2003 and Eskom 2002

Eskom, which is the dominant electricity supplier in South Africa, is a public entity, incorporated as a company in July, 2002. It has a nominal generation capacity of 42.0GW and a net generation capacity of 39.8 GW (Eskom, 2002:130). Other electricity producers, which include municipalities and private generators, produce a total of 3.2 GW bringing the total licensed capacity in South Africa to about 43.0 GW which is equivalent to about two thirds of the entire generating capacity in Africa. South Africa supplies an equivalent of 60% of all electricity consumed in Africa (GoSA, 2002:432).

Eskom has 24 commissioned power stations, of which 13 are coal fired power stations, which produced up to 37, 678 MW in 2002 (Eskom 2002:132). Other sources of electricity in South Africa include one nuclear powered station with a capacity of 1,930 MW, 6 conventional hydro-electric power stations producing a combined 661 MW, 2 pumped storage hydro-electric schemes with a combined capacity of 1,400 MW and 2 gas turbine stations with a combined capacity of 342 MW (Eskom, 2002:132). Coal fired electricity generation dominates the South African power sector, providing over 90% of the electricity generation mix. In addition, there are mothballed coal power stations with a total capacity of 3,556 MW and an estimated 1,426 MW under construction (EIA, 2002). Private producers generate about 4.4% of South Africa's electricity and use a varying range fuels, including coal, bagasse and other agricultural wastes, to generate electricity mainly for their own use.

Municipals and other distributors account for about 41% of all distribution whilst ESKOM distributes the remaining 58% of the generated capacity (Eberhard, 2003).

Like Malawi, the South African power sector is undergoing reforms. Power sector reform goals in South Africa include the rationalisation of a previously highly fragmented electricity supply industry and improving electricity access to communities that were previously disadvantaged by apartheid policies. Like Malawi, the power sector reform process is ongoing in South Africa and the country is moving towards possible partial privatisation of Eskom. To assist in the governing of the power sector, the National Electricity Regulator (NER) was set up in 1995 to oversee issues pertaining to electricity pricing and tariff setting, licensing of participants in the electricity market and resolution of customer complaints and disputes among stakeholders in the electricity sector.

South Africa, like Malawi, is a member of the Southern African Power Pool (SAPP) but unlike Malawi, the South African electricity network is interconnected to SAPP member countries including Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe, to which it sells power, as well as the Democratic Republic of Congo (DRC) and Zambia from which it imports power (SAPP, 2002).

4.3 Drivers and results of the South African electrification process

In 1990, electrification levels in South Africa stood at 33% (Dingley, 1990: 22) representing 51% of the urban population with access to electricity and 13% of the rural population with access to electricity. In the early 1990s only about 10% of black South Africans outside homelands had access to electricity (Theron,1991), leading to high dependence on firewood, paraffin, coal and liquefied petroleum gas (LPG) among black South African households while access to electricity in white South Africans' households was almost universal and its use averaged 700kWh/month (Horowitz, 1994:8). The efforts to address the problems of limited access to electricity resulted in numerous consultations that included government, unions, energy industries and experts, consumers and civil society. As a result of these consultations, the National Electrification Program (NEP) was established. Although efforts to improve access to electricity in South Africa started before the dispensation of democracy in 1994 due to a changing political scenario in South Africa, the electrification process, was intensified after the country's first all-inclusive democratic elections in 1994 and was a part of the new government's development program.

The Reconstruction and Development Program (RDP), a socially orientated program aimed at addressing racial inequalities, was set up in 1994 by the new African National Congress (ANC) government as a framework to mobilise people and resources and formulate development programs, policies and strategies aimed at meeting people's basic needs, developing human resources and building the South African economy among other things (ANC, 1994:7). It aimed

at improving access to physical infrastructure and social services including electricity, land, housing and water through programs and other efforts to provide these public goods and services especially to historically disadvantaged communities. In the electricity sector, the RDP led to the birth of the National Electrification Program (NEP), which targeted 2.5 million new connections by the year 2000 (ANC, 1994: 33, NER, 2001:5, DME 2003), thereby doubling the household electricity access levels from the 1994 baseline of 34% electricity coverage. Specific financing mechanisms were identified and an electrification fund was set up. According to the RDP, financing of the NEP would be mainly from cross-subsidies within the electricity sector and where necessary, concessionary financing would be provided in particular for rural areas (ANC, 1994:33). Any loan financing from investors and lenders for the electrification program would be underwritten by government guarantee.

Following extensive research, it was estimated that 1.75 million of the household connections, representing 70% of the target number of connections would be made by Eskom, whilst remaining 30% of the target connections would be made by local governments (Borchers et al, 2001). The cost of this targeted electrification was estimated at R1.4 billion per year, of which R300 million would be administered by the electricity regulator, NER.

Between 1994 and 2000, the South African electrification program had met and exceeded the target number of connections and according to Barnard (2001) about 3.4 million new connections had been made by 2001.

4.4 Supply side processes and lessons of the South African electrification program.

The following section discusses the electrification process in South Africa under three key themes, namely; planning, financing, tariff design and supply options. Each sub-section discusses the process and the lessons that the process presents to Malawi. Although both grid and off-grid options were implemented in South Africa, off-grid electrification was only implemented in 2001 and was restricted to rural areas. Since this dissertation is limited to urban electrification, the discussion reviews results of grid –based electrification alone although some mention of non-grid electricity is made for clarity purposes.

4.4.1 Planning and financing of electrification in South Africa

Eskom provided most of the financing of the South African electrification program from its revenues. In 1994, Eskom was providing connection subsidies amounting to an average of R70 per connection (Theron, 1999). Currently, Eskom levies an average of 4% of electricity costs of consumption to cross-subsidise new connections (Borchers et al, 2001). As stated earlier, local

governments bore some of the electrification costs and municipalities contributed to reticulation costs in their areas of jurisdiction. However, to help speed up the electrification process, Eskom refunded municipalities R400 for each new connection made by a municipality and municipal distributors were offered bulk discounts on the basis of their electrification programs (Qase and Annecke, 1999:8). According to Theron (1999), this R400 subsidy scheme was discontinued in 1995. The discontinuity of the R400 subsidy is attributed to the high economic burden that this subsidy imposed on the utility.

One lesson from the South African electrification experience is the need for wide consultations, detailed research, planning as well as the presence of political will and commitment to the electrification program. Apart from acknowledging the importance of electrifying the poor in achieving developmental goals and social balance, the South African government has been committed to developing a comprehensive electrification policy and has supported the policy with action and budget allocations from specific sources of funding.

Eskom has been able to finance a large part of the electrification program, including research is because of its sound financial performance and this highlights the need for good management and financial performance of service providers in implementing successful electrification programs.

The South African experience shows that most poor households require subsidies to be able to afford electricity connections. However, if not well designed, these subsidies can be burdensome to the utility, hence the change in subsidy strategy in South Africa. The financing of electrification from levies, which Eskom now pursues, ensures a continued and less burdensome source of funding of electrification. In addition, involving other stakeholders, in this case, municipalities in financing electrification programs spreads the economic burden of pro-poor electrification program, thus reducing any negative financial impacts on the utility. The refunding of part of the municipalities costs by the state-owned utility shows the state's commitment to electrification and motivates other service providers.

Monitoring and evaluation of electrification programs, which were built into the electrification plan in South Africa have been continuous and have resulted in adjustment of design parameters where assumptions made at the design stage of the electrification program are not valid in practice. Such corrective measures, taken in accordance to emerging evidence are crucial in limiting continuation of costly and less effective electrification strategies.

4.4.2 Technology options used in South Africa

A number of pro-poor technologies have been used in South Africa's electrification program. The technologies used were aimed at easing payment of electricity, reducing wiring and

reticulation costs and matching supply standards to demand characteristics of poor households among other things. The technologies used to electrify the poor in South Africa included the following;

- Pre-payment meters which enables poor households to buy certain amounts of electricity as and when they can afford to do so (pay-as-you-go). This is helpful in easing households' control over their energy budget and in reducing the utility's bad debt and lowering administrative costs of revenue collection. The minimum amount of electricity that can be purchased ensures that the administrative costs are covered.
- Compact ready boards, which were used in combination with pre-payment meters, enable utilities and customers to reduce the costs of wiring a house.
- Looped service connection which allows several consumers to be connected from one service cable, thus reducing reticulation costs
- Use of a lower After Diversity Maximum Demand (ADMD), which helps reduce reticulation costs by matching supply characteristics to the low demand patterns of poor households. ADMD is the average demand per customer at the time when the maximum demand occurs on the network (Kotze and Barnard, 2002:50) and is based on estimated load after electrification as given by maximum demand of the electrified households divided by number of households in the area. Since networks are designed to cater for average maximum demand per customer at the time of peak (Kotze and Barnard, 2002:50) and because newly electrified, low income households have lower demand patterns, lowering the ADMD helps utilities to optimise the distribution system and lower distribution costs. The ADMD can later be upgraded if there is an increase in demand.
- In other cases, Aerial Bundled Conductors (ABCs) were used in the transmission system. These are low voltage, overhead transmission systems which reduce maintenance needs and costs, are safer due to insulation and require lesser clearances from trees and buildings. These attributes enhance safety and require less "landscape modifications", aspects which are important in poor urban areas, where houses are often built very close to each other and the settlements are not planned.

The electrification program also used load limiters that allow varied supply capacities. These supply limitations are linked to differentiated tariff levels, to enable consumers to choose the capacity depending on their potential electricity demand as well as their income and expenditure patterns.

The use of varied supply technologies and standards to match the characteristics of the poor while reducing the costs of supply for both the supply and demand side is a valuable lesson for Malawi. Whilst the use of compact ready boards reduced connection costs for the poor households in Mbayani, there is need to explore more opportunities that other pro-poor supply technologies and special standards offer both the utility and the consumers. Technologies that ease the economic burden of paying for electricity, such as pre-payment meter must also be considered. The choice of these technologies should be backed with detailed research to enable the optimum combination of supply options.

Since pre-payment meters offer both ability for households to control their consumption and pay for consumption reflective tariffs whilst reducing billing and other administrative costs and

defaulting, Malawi's future pro-poor urban electrification should consider such technologies but this should be weighed against the extra costs that pre-payment meters may impose on households.

4.4.3 Tariffs design, supply options and cost recovery

In 1994, Eskom developed a tariff known as the S1 tariff which required households to pay a nominal connection fee of R40 (US$ 12 in 1994) and thereafter, the connection fee was recovered through the tariff (EDG, 1995,R3). The tariff also removed the fixed cost component of the tariff, which helps utilities recover their administrative costs. Billing was therefore only for the energy charge which is the charge for the actual consumption of electricity. The S1 tariff was therefore based on Short Run Marginal Costs (SRMC) rather than Long Run Marginal Costs (LRMC). Average connection costs were estimated between R2, 500 and R3, 300 for urban households (Qase and Annecke 1999, NER 2000b). This initial program design assumed that consumption levels would be at an average of 360 kWh per household per month. Following extensive research, it was estimated that at this level of consumption, the fees charged and the associated tariffs would enable the costs of the venture to be recovered in 15 years.

In July, 2003, following studies by UCT, EDRC, Eskom and DME, the DME officially approved and introduced the Electricity Basic Services Support Tariff (EBSST) in order to enable poor households to use electricity for some basic services such as lighting (UCT, 2002, DME, 2003:2). The EBSST entitles households to 50kWh of free electricity per month (DME, 2003:6) followed by increasing block tariffs for consumption levels exceeding the designated 50kWh per month. The implementation of the free electricity has however varied in different municipalities. For example in Cape Town in the Western province, the city council provided 20kWh of free electricity per household per month to all domestic customers in its area of service from 1st July, 2001 (Jones, 2001:36). Later in 2003, the Cape Town city council increased the free basic electricity limit to 30kWh per month per household. Meanwhile, in the City of Tshwane in Gauteng province, the city council initially provided 30 kWh of free electricity per household per month before increasing the amount to 50 kWh per household per 30-days period in July 2003 (City of Tshwane, 2003).

The basis of the tariff design in South Africa is such that higher supply capacities (implying higher demand and assuming higher incomes) are accompanied by higher tariffs and connection fees while low capacities (implying low demands due to inability to afford electrical appliances) are accompanied by lower tariffs and lower connection fees (Table 14). Supplies of 5 Amps and 8 Amps were also used in rural areas at no connection fee.

Capacity	*Connection fee (R)*	*Tariff and principle applied*	*Typical appliances*
<10 Amps Intention is to have the CAPEX[8] of this very basic supply option fully subsidised	Nil	Lowest energy rates. Aimed at making electricity affordable to the poorest.	Radio+lights+television+fridge or one of the following at any one time: iron or toaster or single bar heater or single hotplate
20 Amps Typical consumption: 60 kWh to 120 kWh per month	Capped at R150	Same tariff rate as <10 Amps capacity	Radio+lights+television+fridge or one of the following combinations at any one time: (iron + double hotplate) or (kettle + single bar heater) or (iron + two bar heater) or small geyser
40 Amps Typical consumption: 120 kWh to 800 kWh per month	Capped at R500	Tariff rates higher than 10 Amps and 20 Amps but lower than 60 Amps	Radio+lights+television+fridge + iron + toaster + heater + stove + geyser + washing machine + microwave at any one time
60 Amps Typical consumption: >800 kWh per month	Capped at R1000	Highest tariff rates	Radio+lights+television+fridge + iron + toaster + heater + stove + geyser + washing machine + microwave at any one time. Basic handyman's tools, including welding machine; small business such as a Spaza shop

Table 14: Supply options for single phase grid connections used in South Africa
Source: Adapted from Kotze and Barnard, 2002

Distributors such as municipalities however implement different tariffs depending on their discretion, provided the regulator approves the tariffs. The average net price for electricity charged by Eskom for its residential customers stood at 33.43c/kwh and 14.09c/kWh for redistributors such as municipalities in 2002 (Eskom, 2002:135).

A lesson that the tariff design in South Africa provides is the need to carefully design tariffs and subsidies in line with the characteristics of the consumer and to ensure that the subsidies provided are recovered, if possible, across consumer categories. Lower connection costs and tariffs for low consumers help poor households to gain access to the network and pay lower tariffs in line with their income levels and use of the network. The system used in South Africa also ensures that subsidies are self-selecting such that upon exceeding a certain level of consumption, the consumer is assumed to able to afford certain appliances and no longer benefits from the subsidy. The subsidy design also ensures that high consumers pay for the subsidy provided to lower consumers and hence limits revenue losses on the part of the utility and ensures recovery of subsidy costs.

The pre-payment meters used in South Africa have an advantage over the flat rate tariff in Mbayani in that it eases payment of electricity and reduces billing administrative costs while providing an incentive for energy conservation, which is especially beneficial for the utility. It

[8] Capital expenditure

should be noted however that energy conservation is not a function of household bills only but is affected by users' knowledge among other factors. Use of pre-payment meters and consumption reflective tariff also has a more positive impact of utility revenues, depending on the basis of the tariff structure, compared to flat rate tariff where households may end up consuming more than the cut off point, indicating revenue loss for the utility.

4.4.4 Use of private-public initiatives in South Africa

One other innovative supply option used in South Africa to electrify poor urban households is the use of a public-private initiative. This has been implemented in the Western Province in an urban township called Khayelitsha. Although the case of Khayelitsha is not typical of the South African electrification program in that the South African electrification program was carried out by the public utility, the uniqueness of using a private-public joint venture in providing electricity services to the urban poor offers an opportunity to assess the viability of pro-poor urban electrification initiatives that have limited or no public subsidy support. It also offers an opportunity to test current thinking, which favours increasing the role of private participation in electrification in developing countries and explore diverse electrification strategies.

One objective of the Khayelitsha electrification program was to 'provide urban infrastructure in support to economic development of Khayelitsha as part of the Greater Cape Town Metropolitan Area and thereby raise the standards of living and contribute to the protection of the environment' (Qase et al, 2001:4). Another objective of the project was to demonstrate that 'sub-economic electrification and distribution management could operate as a normal business and make positive cash returns' (NER, 2000a:8). The project was launched in 1994 and was expected to run for at least 5 years, electrifying 33, 000 households between 1994 and 1997 (Qase et al, 2001: 4).

Electrification in Khayelitsha was undertaken by a joint venture company called Phambili Nombane (PN), which in the local Xhosa language means "forward with electricity". The shareholders of PN include Eskom of South Africa, Electricité de France (EDF) of France and Eastern Midlands Electricity (EME) of the United Kingdom (UK) now known as PowerGen (PN, 1999). The two key objectives that drove the PN program are of special interest for Malawi because of the high poverty levels in urban areas in Malawi and the fact that Malawi faces environmental problems caused by, among other things deforestation, which is partly a result of energy needs in households. In addition, since the on-going power sector reforms in Malawi advocate private participation in the electricity supply sector and the need for positive cash returns, it is important to garner lessons on the potential of public-private initiatives in providing electricity to poor urban populations and without compromising the financial integrity of service providers.

The Khayelitsha electrification process

Household connection costs in Khayelitsha were estimated at R2, 700 per household and the total cost for electrifying 33,000 households was estimated at R155 million (Qase et al, 2001:4). The actual costs per connection were however lower than the original estimate at R2, 370 per household, which reduced the actual expenditure to R87 million (Qase et al, 2001:4).

Initially, households were electrified using capacities of 60 Amps at a connection fee of R45 until 1999. From 2000, households were given the option of a limited supply of 20 Amps, at a connection fee of R150 or a supply capacity option of 60Amps at a connection fee of R1000 (Qase et al, 2001:9). The change in the supply strategy seems to have resulted from the realisation that electricity consumption among newly electrified poor households remained low over long periods of time after electrification and the capacity of 60 Amps was often not optimally used. Meanwhile, a 20 Amp supply capacity is cheaper and satisfies certain needs of the consumers including lighting and thermal applications such as cooking and space heating. The higher connection charge of R1000 for 60 Amps supply capacity therefore aims at prompting poor households who are likely to have low consumption patterns to choose a cheaper 20 Amps supply capacity while those that have higher incomes and consumption levels can select the 60 Amps supply capacity. This rationale in consumer supply choices assumes that income is a major determining factor in acquisition of new appliances, which will then boost consumption levels. All the households electrified under this initiative in Khayelitsha have pre-payment meters and compact ready boards.

To assist new users in understanding electricity, community meetings were held in Khayelitsha to discuss electricity use and safety (NER, 2000a:8). Dramas, drawing competitions and provision of electricity information packages to all customers were used to enhance understanding. In addition, there was continued regular distribution of information brochures, help with application of electricity connections and training on safety and economic use of electricity. To improve service delivery, PN has specified response times for faults and inquiries. Data capturing technologies were obtained mainly from France and are used to track changes such as erratic consumption or sudden bill changes that might indicate electricity theft and to assist in tracking faults (NER, 2000a:8). Vending of electricity is done by community based vendors, throughout the township, who are then provided with 2.5% commission for the sales and R300 to cover expenses for depositing the cash collected (Scott, 2003:8), thereby creating new ventures and jobs in a community with high unemployment rates.

One disadvantage of the private-public initiative used in Khayelitsha is that the consumers under this initiative do not benefit from the free electricity provided under the EBSST. The Khayelitsha consumers have also experienced technical problems with the magnetic card pre-

payment meters. Half of the magnetic card pre-payment meters failed and had to be replaced and the rest are expected to be replaced within the next two years (Qase et al, 2001: 11).

The PN public-private partnership has been useful in enhancing financing, reducing risk by spreading responsibility and providing a diverse human resource base. Economic analysis of the program however showed that the Khayelitsha program is not financially viable to service providers although PN remain a profitable venture (Qase et al, 2001: 32). This means that public-private initiatives will require incentives if they are to consider electrification of poor urban areas. In Khayelitsha, Qase et al (2001:33) estimate that a subsidy level of about 2.3c/kWh or R3.44 per customer per month would be required. The implication for Malawi is that there is potential in urban areas for public-private partnerships. However, the economic situation of the poor in urban areas erodes the financial viability of electrification programs. Use of public-private initiatives in electrification programs should therefore only be used where the initiatives will help build capacities of the public service providers and if the subsidies and incentives that will be required by the initiatives do not have an adverse impact on the financial situation of the subsidy provider.

4.4.5 Conclusion of South Africa's supply side review

The supply side review of the South Africa experience provides a number of lessons for Malawi. Firstly, electrification requires that the implementing utility should be effective, efficient and should have adequate financing capacity. Planning should be detailed and financing sources should be broadened to reduce risk and because funding by utilities only is often inadequate to meet the high demand for affordable electricity in poor urban areas. Planning should also address consumer needs. Monitoring should be continuous and where necessary, program design must be changed to suit circumstances in accordance with emerging evidence. The poor in South Africa also showed low consumption signifying that despite the subsidies provided, there were other barriers, which hinder households from using electricity. Provision of targeted subsidies therefore remains a crucial [but not the only] way of improving electricity affordability. Various cost-reducing technologies and supply options must be researched and implemented and public-private initiatives must be explored and where necessary, these must be used to enhance service delivery capacity.

4.5 Demand side processes and lessons

The electrification of poor households in urban areas brought a number of changes in household energy budget control, fuel use patterns and other socio-economic factors. The following sections discuss the impact of the electrification process and its tariff design on the demand side in South Africa and the lessons it provides for Malawi.

4.5.1 Electricity payment modes in South Africa

Payment for electricity in South African poor urban areas is based on tariffs that are matched to particular supply capacities. Households are installed with pre-payment meters and households buy electricity credits as and when they can afford it. Pre-payment electricity units are sold by various selected vendors in the communities, shops and service stations in residential areas (Scott, 2003). This is convenient since it reduces the need to go to the utility to pay for electricity and also provides opportunities for kiosk owners in poor urban areas to diversify the income base since they get a commission from the sales of electricity.

In addition, pre-payment meters provide some control over the electricity budget compared to credit electricity metering since households buy electricity as and when they can afford. Despite this benefit, disruptions in cash inflows in the course of the month may mean that households' electricity supply may be disrupted if they cannot afford to buy electricity at a particular time. Pre-payment meters also offer limited ease of payment in that households have to ensure consistent income flow through out the month. In this respect, the flat rate tariff is more attractive since income disruptions within the month do not affect electricity supply and households can plan and save through out the month because they are always aware of the electricity bill. Nevertheless, unlike the flat rate tariff, the tariff structure used in South Africa does not subsidise high electricity consumers at the expense of low electricity consumers and so unlike the tariff in Mbayani, the tariff in South Africa does not exacerbate the vulnerability of poorer households.

Qase et al (2001) argue that the lessening of women's burden due to quicker and easier cooking with electricity, is dependent on households' ability to buy electricity for adequate amounts. This would imply that the flat rate tariff design used in Mbayani is more effective in decreasing the work burden related to lack of access to electricity. This is because households are able to use adequate amounts of electricity without straining their financial resources further and are therefore more likely to use electricity for cooking and other activities. This would however be dependent on other factors including the households' ability to buy and use electrical appliances (in particular, cooking appliances).

4.5.2 Fuel use strategies and choice

Although pre-payment meters offer a flexible paying option, electricity remains an expensive commodity for customers in poor urban areas in South Africa. In Khayelitsha for example, electricity is considered too expensive for thermal applications (Qase et al, 2001). As a strategy to curb electricity expenses, households tend to use other fuels such as paraffin or gas in Khayelitsha and coal in most townships in Gauteng province, for cooking foods that take long to cook (hard foods such as beans) and electricity for foods that take a short time to cook (soft

foods such as leafy vegetables). This contributes to the use of multiple fuels in electrified poor households. In Mbayani, the 15 Amp supply capacity option, coupled with a flat rate tariff partly addresses the issue of multiple fuels use resulting from concerns over expenses due to usage of thermal appliances since households can use electrical appliances and have higher consumption without worrying about higher bills.

As is the case in Malawi, use of multiple fuels remains prevalent in South Africa because of low incomes, which hinder households from purchasing electrical appliances (Theron, 1999). According to Theron (1999), about one fifth of the electrified households still used paraffin and gas for cooking in 1999, with more dependence on electricity observed in households that had been electrified earlier. Use of paraffin lamps and candles for lighting in electrified households in poor urban areas in South Africa is attributed partly to structural limitations of the compact ready board, because there is no wiring and so only the room with the compact ready board is lit (Mehlwana and Qase, 1996:11-12, Simmonds, 1996: 37) while continued use of gas and paraffin or coal in poor electrified households is attributed to the households' inability to afford electrical appliances (Qase et al, 2001). Simmonds (1996:34) also attributes continued use of previously used fuels to 'fear of the unknown' and social relations and even appliance purchasing conditions. Unlike in poor urban areas in South Africa such as in Khayelitsha where households have left some of their rooms without lights, depending entirely on the light bulb supplied with the compact read board, in Mbayani almost all the households interviewed had extended lights to almost all rooms, using extension cords and other wiring strategies.

The continued use of pre-electrification fuels prevalent in both South Africa and Malawi indicate the need for energy policy to continue investigating and promoting use of various efficient household fuels. In Malawi, these are likely to include improved cook-stoves. It also indicates the need to promote low-cost electrical appliances, since low purchasing power limits households' ability to acquire electrical appliances. Provision of electrical appliances on credit should be considered as an optional extra for households. In addition, better low-cost wiring techniques should be considered. Some developing countries have used harnesses to extend wiring from a compact ready board to other rooms in the house at low costs. Service providers should also continue to engage in dialogue with consumers to allay fears of electricity.

4.5.3 Effects of electrification on micro-enterprises in South Africa

A study by Fakira (1994) on the effects of electrification on micro-enterprises in South Africa showed positive contribution of electricity to the SME sector. One effect that was observed was the 'significant reduction in energy expenses in different income groups' in micro-enterprises (Fakira, 1994:24). This reduction then means that there is an increase in profit margins of the entrepreneurs, thereby boosting their incomes. Another change was the redistribution in micro-

enterprise sectors. There was a diversification in the goods and services, which would entail that new business sectors and therefore, new income generating opportunities were opened up. This is because some businesses that require electric power were opened up or expanded.

In one area, increased efficiency was reported by one of the welders who used petrol powered generators before electrification. This led to a doubling of output, which may imply increased profitability and to match this increased output, the welder employed assistants, which then created employment (Fakira, 1994:24). In another case, a baker reported improved efficiency and reliability. This improved his image among customers and increased his output. As a result, the baker increased his employee base from four to twenty-four (Fakira, 1994:25). Other benefits were observed by butcheries, shops and other traders. Most of these were able to buy new equipment that operates on electricity and improved their output levels.

Fakira (1994:22) however attributes part of the significant growth in micro-enterprises to an injection of capital in the micro-enterprises from financing institution.

In Khayelitsha, the use of community members to vend electricity tokens resulted in about 27 vending stations in the area (Qase et al, 2001:27). Most of these vending stations are home based because community members were against the use of already established businesses (Qase et al, 2001:27), probably in an effort to "create" new entrepreneurs. Despite the fact that these have introduced new businesses in the area, there have been concerns over customer services, due to lack of business skills training (Qase et al, 2001:27).

The experience in South Africa implies that electricity has potential for contributing to the development of the SME sector in poor urban areas. However, to enhance these benefits, there is need for programs that support the emergence and growth of business. This support should include credit facilities and business skills training.

4.5.4 Conclusion of South Africa's demand side review

Like in Malawi, the largest shifts in fuel use were observed in lighting and media applications and continued use of multiple fuels is observed especially in cooking. This and the lower than expected consumption in South Africa is mainly attributed to households' inability to afford appliance, especially cooking appliances and underscores the need for exploring resources for providing low-cost electrical appliances to newly electrified poor urban households. It also calls for the development of strategies to promote efficient use of other fuels in the period of transition from traditional fuels to electricity.

Although the flat rate tariff used in Mbayani seems to offer better budget control than pre-payment meters, pre-payment meters have more balanced benefits, both across households of different income levels and for the implementing utility.

Use of private-public initiative has some benefits for capacity building and must be explored in Malawi. However, it is important to ensure that consumers under such programs are not disadvantaged by private operators' need to profit. Benefits that accrue to consumers supplied by public-private initiatives must offset any disadvantages that public-private initiatives may impose on these consumers. In the case of South Africa, arrangements can be made to ensure that PN consumers also benefit from EBSST or have other benefits that substitute the benefit from the free basic electricity.

The literature review has shown the benefits of electrification in micro-enterprises. However, there is need for supporting these micro-enterprises in order to enhance benefits.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5. Introduction

The study has investigated, within its defined parameters and within the constraints faced, the benefits and costs of the Mbayani electrification program on the supply and demand side. It has found that the program design is not beneficial to the utility and may in the long run, or when carried out on a large scale, have a negative impact on the revenue intake of the utility. This is mainly attributed to unsustainable financing, narrowly focussed planning and poor tariff design. On the demand side, the study has established that there are net benefits for users. These benefits include cash savings due to changes in fuel use, reduced energy burden and better budget control, changes in fuel use from low quality fuels to electricity, increased appliance ownership and benefits that have accrued to small businesses among others. Despite these benefits, there are certain aspects of the program design and prevailing socio-economic situations that are hindering households from maximising the benefits from the low cost electrification program. These include high costs of electrical appliances, unreliable electricity supply, poor quality appliances and lack of dialogue between service providers and electricity users. Benefits to the SME sector in Mbayani are limited by the fact that connections are restricted to household use and there is lack of support for SME development.

The review of the South African electrification program has provided some valuable lessons for Malawi. These lessons include the need for specific financing for electrification programs, the need to explore a wide range of cost-reducing technologies and need for detailed research and planning in coming up with tariff design and supply options. The South African review has also shown that there is potential for public-private initiatives in electrifying the urban poor which should be explored because they can enhance capacities. The South African experience also shows that electricity has benefits for the SME sector, which include efficiency gains, increased outputs and employment creation.

The next section discusses the specific conclusions resulting from the study findings and makes policy recommendations based on these conclusions. It also briefly discusses some of the challenges that would arise from implementing the policy recommendations.

5.1 Supply side benefits and costs

5.1.1 Program financing and planning

Depending solely on utility financing is unsustainable and narrowly focussed top-down approach to planning limits the benefits to the utility.

The Mbayani low cost electrification program was financed entirely from utility revenues, which is a positive development compared to the traditional reliance on loan financing for electrification. However, while it is encouraging and desirable for the utility to source electrification financing from its revenues, this is not a sustainable source of finances for large scale programs because poor urban areas in Malawi have a large electrification burden which is compounded by rapid urbanisation. In addition, utility funds are in local currency, which is weaker and unstable while over 80% of the utility's costs are in foreign and stronger currencies such as the US dollar while revenues are in Malawi Kwacha. This means that profitability is eroded [by the conversion]. This implies that ESCOM may not be able to sustain larger scale urban electrification programs from its revenues alone.

To ensure that urban electrification programs are financially sustainable, policy and service providers must diversify sources of sustainable funding. Such sources may include instituting a levy from electricity sales, which can then be used to contribute towards subsidisation of upfront costs. Disbursement of these funds should be transparent to avoid corruption. In addition, the use of the funds should be monitored and matched with the electrification progress.

The lack of a guiding pro-poor urban electrification policy and lack of detailed planning before implementation of the Mbayani low-cost electrification program are also limitations in designing effective low-cost electrification programs that maximise benefits for the utility. The cost and benefits analysis carried out before the implementation of the program was inadequate because it was exclusively from a technical (engineering and economic) perspective on the utility side but ignored the user side needs.

The utility and the Department of Energy must draw up policy guidelines for pro-poor urban electrification to ensure detailed planning before implementing electrification programs in order to improve outcomes. Participatory planning and demand side cost-benefit analysis and needs assessment must be encouraged to ensure that needs of target communities are incorporated in plans.

5.1.2 Supply options and technology

Use of compact ready boards to electrify the poor is beneficial in reducing costs and more cost-reducing supply and other technology options should be explored and used where appropriate.

One benefit from the supply side is that lower costs of using compact ready boards to electrify households encourages the uptake of electricity among poor urban households while enabling ESCOM to use infrastructure that was being underutilised and obtain revenue from it. Amortisation of capital costs of connection and the compact ready boards makes access to electricity easier for poor households that cannot afford to pay upfront costs of electricity. This benefits the utility in that it increases its customer base and subsequently, its revenue base and uses previously under-utilised infrastructure. The use of compact ready boards also reduces wiring costs further encouraging the uptake of electricity in Mbayani.

However, the fact that ESCOM only considered one supply capacity and technology option without the benefit of comparative analysis and lack of consumer needs assessment implies a narrow focus that may have led to implementation of a program that is likely to be less effective than alternative options that could have been discovered if detailed analyses were carried out before implementation.

The utility must continue to use innovative technologies and supply options that lower costs on both the demand and supply side. This can also include rationalisation of standards to match the demand characteristics of the urban poor, as has been the case in South Africa where households are offered varying supply capacities depending on their needs and socio-economic situations.

5.1.3 Tariff design and its effect on cost recovery, revenue intake and consumers

The tariff design ensures cost recovery of compact ready board costs but the lack of responsiveness to consumption limits cost recovery of actual electricity consumption. In addition, the tariff design subsidises high electricity consumers at the expense of low electricity consumers.

One advantage of the flat rate tariff on the part of the utility is that it is easy to administer since it is the same for all consumers. However, it is unclear how this tariff level was decided upon and unavailability of data on this tariff design precludes further analysis.

In terms of cost recovery, the tariff design ensures the recovery of the costs of the compact ready board unit for each household after five years. However, it does not guarantee recovery of costs of actual energy used per household since it does not reflect consumption. There is likely

to be under-recovery in households, which have higher consumption, and over-recovery in households with lower consumption. This implies that low consumers, who are more likely to be poorer households subsidise high consumers.

Under-recovery of costs of actual energy used is likely to increase with time because users are likely to obtain more appliances. The resulting increases in electricity consumption are likely to cause revenue losses over time since it is not easy to match these changes with tariff adjustments. This trend of increasing consumption has been observed in South African poor urban areas and other countries, which have monitored electricity use trends over time in, electrified homes in poor areas. Although any revenue losses can be ameliorated through monitoring of consumption trends and appliance acquisition trends, the lack of meters and monitoring and evaluation studies of the electrification program in Mbayani means that ESCOM may not be well informed about the changes in consumption in the area.

Since it is unclear how ESCOM deals with customers who are paying more than the allocated monthly charge, ESCOM may over recover from some of these customers. It was also unclear whether depreciated costs of the existing network are fully accounted for in the tariff due to lack of data.

The effect of the flat rate tariff design on ESCOM's revenue is unclear due to lack of data. It is however likely that the tariff design has a negligible effect at the scale that the program is currently implemented since the customer base of the Mbayani low-cost electrification program is less than 0.5% of the entire ESCOM customer base. However, if the flat rate tariff design is to be adopted for large scale pro-poor urban electrification programs, the effect is likely to be negative because the tariff design does not respond to consumption, yet the capacity limit of 15 Amps allows most applications to be carried out, including cooking which contributes a high load of electricity at household level.

There is need to redesign the tariff so that it closely reflects consumption and to reduce its adverse impacts on the utility's revenue base especially for large scale electrification programs. In rationalising the tariff, efforts should be made not to exacerbate the vulnerability of poorer households by subsidising high-level consumers.

The flat rate tariff should be replaced by pro-poor tariffs such as pricing low levels of consumption based on SRMC, and higher levels of consumption at LRMC. Thus only high consumers, who are likely to be high income households, contribute to future network investment costs while poorer households contribute only to recurring operation and maintenance costs, cost recovery of their connection and the actual energy they use per month unless they consume more than the level where the SRMC pricing cuts off.

Another tariff design structure that can be considered is the single rate tariff, which has no fixed charge, and low-level consumers who are usually poor households are subsidised. The subsidy should reduce with increasing consumption and must stop where the service provider's revenue breaks even. For consumption levels above the break-even point, high-level electricity consumers can then gradually pay for the subsidies awarded to low-level consumers. The single rate tariff is advantageous because it is simple to implement and users share capital investment and fixed charges for the network in proportion to the use they make of the system. In addition, subsidies are paid by high-level consumers, thus reducing the economic burden imposed on the utility. Furthermore, this tariff structure provides incentives for electricity conservation in households.

In implementing these tariffs, the challenges to be addressed will include; determining which income groups to subsidise, how much subsidy to provide and how to graduate or allocate the subsidy payments among the high level consumers. Research will have to be conducted to help decide the optimum tariff and subsidy design and to ensure that the subsidies do not accrue to non-poor households and do not impose a heavy economic burden on the service providers.

5.1.4 Supply side summary of conclusions and recommendations

The study concludes that the low-cost electrification program has net costs to the utility, which are mainly a result of limited planning. In particular there is a single financing source; the utility, whose profitability is not adequate to support the existing urban electrification burden and the future electrification burden resulting from urbanisation. There is no pro-poor urban electrification policy or guidelines and the tariff design is also not suitable for replication in other areas because it does not respond to changes in consumption in a timely manner which can cause substantial revenue losses. However, at the scale it is implemented, costs are absorbed by the utility without significant adverse impacts on its revenue intake.

The study therefore recommends that planning and financing of pro-poor urban electrification programs must be improved and use of pro-poor technologies to electrify poor households must continue. The tariff must be redesigned to better balance the supply and demand outcomes.

5.2 Demand benefits and costs

5.2.1 Household incomes and expenditures

Household incomes and expenditure patterns vary widely but overall, electricity has resulted in a real increase in energy expenditure and decrease in energy expenses in relation to other essential monthly expenses. The increase in energy expenditure is however minimal when inflation and other factors are taken into consideration.

There is a wide variation in incomes levels, sources and distributions as well as household size, which implies varying per capita household incomes. As a result of these differences the benefits and costs of electricity are experienced differently in different households and certain households are more vulnerable than others. The wide variations in income and expenditure patterns imply need for flexible approaches in service delivery to ensure that introduction of electricity does not exacerbate poverty in more vulnerable households.

The overall average household fuel expenditure increase of 6% after electrification is attributed to overall increases in fuel costs that occurred between 2001 and 2003. Furthermore, electricity is largely being used in addition to other fuels and has not fully replaced previously used fuels. Electricity expenses are therefore additional and not substituting previous fuel expenses. Other factors discouraging substitution of previously used fuels by electricity include limited incomes that hinder households from purchasing appliances and unreliability of electricity and electrical appliances.

The 6% increase in fuel expenses, which is well below the monthly food and water expenses at an average of 64% and below the average urban inflation of 20% per year in the same period, between 2001 and 2003, is an indication of the positive effect that electricity has had on fuel expenses in the newly electrified households in Mbayani.

Due to the varying incomes in poor urban areas, urban electrification strategies should offer varied and flexible supply capacities. The varying capacities should allow a broad range of activities and households should be informed about what each capacity can cater for and be given the opportunity to choose the supply capacity that suits their income levels and livelihoods. The scope of electrification should include SMEs since these are an important source of income in poor urban areas and this can enhance households' ability to pay for electricity due to increased incomes and can reduce the energy burden that households have.

Since cooking is ranked as the most beneficial function of electricity, capacities provided should be enough to power electrical cooking appliances such as hotplates. However, the option of lower capacities that allow lighting only should be provided for the poorest households who

cannot afford electrical cooking appliance. Households should however have the option to move from one level of supply to another when their economic situations change.

5.2.2 Effects of electrification on household energy burden and budget control

Electricity has resulted in a reduction in the energy burden and has eased the budget control but the tariff design has a weakness of subsidising high electricity consumers at the expense of low electricity consumers, thereby increasing their vulnerability.

On average, the introduction of electricity and its related tariff design to poor households has reduced the energy burden in the newly electrified households. Although overall fuel expenses increased by 6%, the proportion of fuel expenses in relation to food and water decreased by 9%. In comparison, the expenses for food and water in increased by 7% and 2% respectively after electrification, indicating that despite inflationary increases in fuel expenses, there is a decrease in the energy burden that these costs impose on the households' budgets, which are a result of using electricity. These changes may however, not be statistically significant. The cash savings from reduced energy costs may have been redistributed to other essentials such as food and water, which can then improve the health status of electrified households, as households may be able to afford better quality food and water. The lower energy burden is further attested to by the reduction in energy burden from an average of 22% of total household budgets on fuels before electrification to 17% after electrification. Under the current tariff regime, use of electricity therefore yields cash savings benefits.

The reduction of the energy burden is partly because households are able to use more electricity without increasing their electricity bills and are therefore switching from more costly traditional fuels to electricity.

The monthly flat rate tariff is also beneficial in that it eases the households' control over their energy budgets because households are aware of their bill throughout the month and are often able to plan and save for the payment. The tariff design is especially beneficial to households that have a wider range of appliances and have substituted all or most of their traditional fuel use with electricity.

The cost that the monthly flat rate tariff design imposes on households is that households that have lower consumption than the design consumption level pay more than the cost of their consumption. This subsidises higher consumers who are likely to have higher incomes or higher level of resources per capita and can therefore afford more electrical appliances. Meanwhile, the low consumers who cannot afford more appliances to enable the transition from traditional fuels to electricity, supplement their fuel needs with traditional fuels particularly for cooking

and so have higher energy burdens. This supports the supply side conclusion that tariffs must be redesigned to better balance the benefits of electrification, even among households.

5.2.3 Electricity payments and their effect

Respondents vary the actual payments to ESCOM due to financial pressures, lack of understanding of invoices and erroneous billing. Respondents however find the terms of payment easier compared to paying for previously used fuels.

Respondents find the flat rate easier to plan for and more desirable compared to paying for previously used fuels, because disruptions in cash flow during the month do not necessitate disruptions in fuel supply.

Although terms of payment stipulate that households should pay a monthly flat rate tariff, there are variations in actual electricity payments that households make to ESCOM. This is partly attributed to differences in incomes and also to lack of understanding of the payment requirements of the program. This has raised concerns in some households that households' ready board debt to ESCOM is accumulating interest or other charges.

Poor billing also contributes to households varying their payments to ESCOM and this has raised concerns and caused some household to contemplate disconnections. The lack of indication on invoices of the outstanding payments for the compact ready board unit has raised fears that some households may overpay their dues to ESCOM.

The concerns relating to payments and billing are augmented by lack of dialogue between service providers and users and may lead to increased energy burden in some households who may pay more than they can comfortably afford.

The utility must engage in dialogue with the electrified households in order to reduce anxieties and to educate the newly electrified households about electricity payment and to address concerns that arise from their experience with electricity use. Such forums can also be crucial in establishing goodwill among consumers, which can deter vandalism, thereby reducing maintenance costs resulting infrastructure damage by disgruntled customers.

One challenge that promoting dialogue would present is the setting up of effective forums. Where local institutions such as development committees already exist, these should be strengthened and used as entry points for the establishment of energy committees, to facilitate dialogue between the service providers and members of the community. However, in most cases in Malawi, such institutions are either weak or non-existent, especially where energy is concerned. In such cases, new community-based groups will have to be established to form a base for setting up dialogue.

5.2.4 Fuel strategies and choice

Most households have shifted to electricity use especially for lighting and for radios and partly for cooking but use of other fuels especially firewood and charcoal continue due to high costs of electrical appliances and other socio-economic factors.

A major shift in fuel usage is observed in lighting where all households have switched to electricity, extending wiring to other rooms in their homes. Paraffin continues to be a part of the household energy scenario mainly for igniting brazier fires and as an emergency alternative in cases of power failure. There is a structural constraint in the ready board design which mainly affects lighting because the ready board is installed in one room; usually the kitchen or dining area and the service provider is not responsible for wiring the home. Although, the benefit of (the utility) not wiring the entire household is that it reduces households' costs of accessing electricity, households desire to have electricity in all rooms and so extend electricity to other rooms in their homes using unconventional methods which can endanger their lives.

Pro-poor electrification strategies should encourage use of appropriate technology such as harnesses to extend wiring. In addition, households must be encouraged to have their extensions inspected and certified by utility personnel.

About 68% of the sampled households (including those using electricity in combination with traditional fuels) are using electricity to cook. Use of charcoal and firewood for cooking still persists (even in households with electric cooking appliances) due to the following reasons;

- Some households cannot afford electrical appliances due to their low incomes or competing demands for their incomes.
- Poor households often buy cheaper, low quality appliances; most of which are second hand, and these are often unreliable. These households therefore use electricity in combination with other fuels. In some cases, households switch back to traditional fuels because their electrical appliances have been damaged and repair costs are too high for them to afford.
- Households continue to use traditional fuels to cope with the poor reliability of electricity supply.
- Traditional fuels are sometimes favoured where they serve multiple functions such as the simultaneous use of charcoal as a fuel for space heating and cooking.
- Traditional fuels, in particular, charcoal and the cook-stove (Mbaula) play important social functions as a central point of household interaction.
- A number of households prefer the taste of foods cooked on charcoal braziers than foods cooked on hotplates. Such households continue to cook certain foods, especially beans on charcoal brazier for this reason.

Whilst 88% of households have switched to powering their radios with electricity, 6% of the households still use dry cells and car batteries to power their radios. One contributing factor to the rapid shift to electricity for powering radios is the fact that radios were widely available in Mbayani and most of these have been adapted to mains electricity power. Hence, once

electrified, most households did not have to buy new radios. The major reason for not using electricity in some households where radios were available was the fear of damaging the radios while other households could not adapt their radios for mains electricity. Other households were no longer using their radios because they had since been damaged or stolen. Damage to electrical appliances is attributed to low quality appliances, poor quality supply and limited knowledge in use of the electrical appliances.

Most households do not have television sets, refrigerators or freezers and space conditioning appliances such as heaters and fans. This is attributed to the high costs of these appliances, which households cannot afford. Use of electricity to iron clothes is increasing gradually.

Due to the shift from previously used fuels such as paraffin, charcoal, firewood, dry cells and batteries, households have had benefits that include cash savings, better quality lighting, cleaner indoor air, convenience and improved social status.

Electrification strategies must promote penetration of good quality low-cost appliances to reduce the phenomenon of switching back to traditional fuels due to the costs of repairing or replacing low quality appliances which easily malfunction, and to encourage the shift to electricity use in newly electrified poor households. Energy sector-wide policies should also promote use of efficient biomass stoves and promote the research and use of more efficient charcoal production methods and technologies as well as use of briquettes to help reduce costs of biomass fuels, which are still used after electrification. Other fuels such as paraffin and gas should also be promoted through development of supply networks that provide small quantities, such as refillable gas cylinders to poor urban households.

5.2.5 Appliance penetration, ownership and use

The penetration of electrical appliances is hindered by the high cost of these appliances and other socio-economic factors such as personal preferences of the person who influences decision-making in the household and gender relations.

Acquisition of appliances is affected by a number of socio-economic factors. Major factors are the cost of electrical appliances and the value that households attach to the related services that the appliances offer. Although refrigerators and television sets are highly desired by most households, their high costs are responsible for their low rate of penetration, thereby hindering households from benefiting more fully from the low-cost electricity.

The low penetration of more costly appliances such as refrigerators and to a limited extent; hotplates, indicate the need to assist poor households acquire electrical appliances for example, through credit facilities. There is however little incentive for the utility to provide such credit

facilities and cash flow problems may further erode its ability to provide appliances on credit to its customers. Policy should therefore provide incentives for utility and local entrepreneurs to provide such credit facilities.

High costs of electrical appliances also compel households to opt for cheaper but low performance and sometimes, dangerous appliances, which raises safety concerns and sometimes increases the burden imposed by electrification due to frequent appliance replacement and repairs. Policy must therefore promote the development of local skills in assembly of appliances as one way of ensuring availability of low-cost electrical appliances. Community members must be trained to repair appliances to increase accessibility to repair workshops and to provide cheaper and reliable repair services. Information campaigns must also assist households to identify potentially dangerous electrical appliances.

Another factor limiting the benefits of electrification is the limited knowledge on appliance use and the capacities of certain appliances. As a result of this, certain households have appliances which they do not use. Information campaigns must therefore be used to improve knowledge of electrical appliances and electricity use among newly electrified households.

The lack of direct correlation between household incomes and the number of appliances owned by a household indicates that decisions to acquire appliances are affected by complex socio-economic interactions including knowledge of electrical appliances, personal preferences of the person who influences decision-making in the household and gender and power relations within households. This indicates the need for increased research in understanding how intra-household and inter-household relations affect resource allocation and vulnerability of poor households.

5.2.6 Contribution of electrification to SMEs

Electrification has had positive impact on the SME sector in Mbayani but these are limited lack of targeted support for SMEs.

Although the dissertation does not quantify the contribution of electrification to SMEs in terms of actual increases in incomes or savings by SMEs due to use of electricity, there is evidence that electricity has a positive contribution to SMEs due to extended working (including preparatory) hours, extended trading hours, secure trading environment, value addition and introduction of new ventures that depend on electricity. There were two new businesses that had been started as direct result of electrification. The low level of new businesses that are a direct result of electrification is partly attributed to the short period of time that electricity has been in the area. The two new businesses are however an indication that electrification has the

potential to contribute to development of the SME sector in poor urban areas. The low levels of new ventures may also have been a result of under-reporting of business ventures started as a direct result of electrification since households were instructed not to use electricity for income generating activities.

In the other SMEs which existed in the area before electrification, electrification resulted in diversification of goods and services and extension of trading hours, which may imply increased profitability, increased incomes for the households undertaking these ventures and increased employment opportunities. However this is true only for home-based businesses including some kiosks that are attached to the electrified houses since the electrification program was restricted to households. There may also have been a decrease in cost of inputs in that before electrification, kiosks used paraffin to light up their shops and battery operated radios for entertainment and both these fuels are more costly than using electricity.

The benefits that electricity generates for the SME sector are limited because electrification was limited to households and did not include business premises such as stand alone kiosks, workshops, private schools and clinics. In addition, the program specifically prohibits users from using electricity for business ventures, even home-based businesses. Whilst this is important on the part of the utility as it limits electricity use, which is crucial for the utility in view of the flat rate tariff design, it reduces income-generating opportunities that households may have derived as a direct result of acquiring electricity and hence negatively affects the chances of moving households out of poverty. The fact that only one supply capacity level was used also means that those households that would have wanted to engage in business ventures that require higher supply capacities such as welding are unable to do so. Other factors that limit the exploitation of benefits of electricity in the SME sector in Mbayani is the lack of SME support services such as business skills training, limited access to credit facilities and poor organisation of the SME sector in the area. General economic hardships experienced throughout the country, which means households may not have enough money to embark on new SMEs and buyers' limited purchasing power may also have affected the development of SMEs among electrified households in Mbayani.

In order to maximise contribution of electrification programs to the SME sector in poor urban areas, electrification programs in low income areas should be carried out along with entrepreneurship development programs such as provision of low interest business loans, business development skills through training and removal of other barriers to SME development. Since SME development is not normally the domain of the utility, there is need for a multi-sectoral approach and involvement of other development partners.

Where possible, electrification related business ventures should be encouraged. These may include the training of local personnel in assembly and repair of appliances, which have related benefits of reducing the cost of appliances and make it is easier for households to access repair shops, whilst creating employment. Another way of contributing to the development of the SME sector is to involve community members in electricity installations (e.g. providing labour) and hence contributing to gainful employment and new SMEs in the target community members as well as skills transfer.

5.2.7 User's perceptions of benefits and costs of electrification

Users ranked cooking as the first most important benefit of electrification and the high cost of appliance as the biggest challenge to benefit from electricity.

Respondents ranked cooking with electricity first as the key benefit of acquiring electricity, in particular the reduction in cooking fuel expenses, which frees money for other household expenses. In addition, the residents observed an improvement in the ease and speed of cooking which is especially important for women who no longer have to struggle making fires. This then frees up some time for women to engage in other productive activities and in some cases gives them time for leisure. Changing from cooking with charcoal and firewood may also have spill-over health benefits due to reduced indoor air pollution.

Respondents ranked information acquisition as the second key benefit of electricity. They felt that the reduction in expenses resulting from dry cells or car battery usage has contributed to increased access to information especially by radio, entertainment and increasing cash savings. Increased access to information may also contribute to the community's ability to make informed choices and promote a sense of social inclusion. Respondents ranked sense of security that lighting provides as the third most important benefit.

Reading resulting from the better quality of lighting which electricity provides was ranked as the fourth most important benefit. Although respondents acknowledged that better lighting was conducive to study for their school-going children and may in the long term have spill-over effects resulting in better academic performance, most households felt that lighting benefits for reading were general in the household. Respondents felt that children's interest in studies and the quality of education available to them were more important deciding factors in whether or not children would extend studying hours once their homes have been electrified.

Linkages were observed between costs of appliances, penetration rate of appliances in the community and the rank, hence value of the services offered by a particular appliance.

Constraints that households face in the order in which they were ranked by the respondents were; high cost of appliances which compels households to use multiple fuels, unreliable electricity supply, high tariffs, lack of dialogue between service provider and consumers, poor billing and supply capacity constraints. In addition, most appliances that households can afford are of low quality and need frequent and costly repairs and are hazardous to use.

Poor supply reliability and lack of dialogue has contributed to loss of goodwill, resulting in frustrations that have led to households either contemplating disconnection or defaulting on their payments and in other cases, people have vandalised ESCOM infrastructure. The lack of dialogue is well illustrated by the fact that the utility feels that the program is not suitable for poor urban areas and does not want to expand its implementation, while the recipients feel that the program is beneficial to them and should be expanded, albeit with some changes due to problems they have experienced with the current program. Lack of dialogue is also reflected in the growing misunderstanding on tariffs and billing. ESCOM must therefore establish communication channels and dialogue. This not only benefits users by improving services but also benefits the utility in that it may limit incidences of infrastructure damage which are costly for the utility and may discourage defaulting, which results in revenue losses.

The utility should therefore improve services delivery through, among other things, developing performance indicators for supply and service quality. Responsible utility personnel and departments must then meet the targets of these service quality indicators to ensure the provision of adequate levels of services. Indicators for electricity supply reliability must aim at reducing frequency of power shortages (measured by number of outages or power interruption per month), average duration of power outages per month and average length of time between fault report and corrective response.

Key challenges in improving service delivery may include lack of information to develop realistic benchmarks. In other cases, specific and measurable indicators may not be quantitative and may be difficult to formulate. In such cases, proxy indicators may have to be used.

5.2.8 Demand side conclusion

The study concludes that the low-cost electrification program has net benefits to consumers despite a number of problems. One major benefit of the program is that the use of compact ready boards to electrify households lowers costs of electrification by lowering wiring costs, which constitute the largest cost of electrification at household level. This makes electricity available to poor urban households who may otherwise have been unable to afford electricity and to houses constructed by mud, which cannot meet the conventional wiring standards since the walls are not strong enough to accommodate conduits for wiring.

The use of a monthly flat rate tariff has eased households' control of their energy budget and to an extent improves affordability of electricity among the urban poor thereby enabling households to shift from traditional fuels to electricity. However, the tariff design has the disadvantage of subsidising high consumers at the expense of low consumers and is a disincentive to electricity conservation.

The study also shows that electrification has had a positive effect on SMEs in Mbayani, although these benefits are limited by some barriers including supply capacity constraints, restriction of electrification to households, limited SME support infrastructure and lack of credit facilities.

In general, the study illustrates that maximising benefits of electricity for the urban poor without compromising the financial integrity for the electricity service provider is a complex issue that requires a multi-faceted approach.

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APPENDIX 1: GLOSSARY OF TERMS

Amortise – A systematic reduction in lump sum amount [of debt] by making a series of payments, usually comprising a principal amount and interest.

Apartheid – Former policy of racial discrimination exercised by the South Africa government

National income- Sum of all individual incomes in an economy, earned as wages, interests, rents and profits, excluding government grants and calculated before tax deductions.

Compact ready boards – Low cost electrical unit consisting of a bulb or bulb holder, sockets and circuit breaker, used to install electricity in households without the necessity of wiring.

Electrification burden – Number or percentage of households that remain without access to electricity in a particular area.

Energy burden – Energy expenses, expressed as percentage of total household expenditure, used to assess the amount of money spent on fuels in relation to other household expenditures.

Fixed charge – A charge that is part of the tariff and is independent of consumption level. It is used to cater for cost of services including administrative costs and costs of operation and maintenance of the network.

Flat rate tariff- Fixed charge for consumption of electricity per unit time [such as per month] regardless of amount of electricity used. Usually used when electricity is not metered.

Electricity sales levy- A statutory payment, usually a fixed percentage of sales of electricity paid into a fund.

Lifeline tariff- A tariff that is below costs of supplying electricity, designed to benefit poor households who cannot afford electricity supply at cost.

Long Run Marginal Costs (LRMC)- Incremental costs of adding a unit of power to an electricity system. Tariff structures based of LRMC take into account the cost of current operating costs and planned future (i.e. long run) investments, so as to avoid excessive electricity price increases when adding capacity to the system.

Management contract – A contract whereby an entity out-sources its managerial functions but retains its ownership of assets, usually to improve its performance.

Nominal capacity- Maximum power that an electricity-generating unit can produce, as specified by the manufacturer.

Outliers- Observations or points of data, that differs substantially from the rest of the data. They can be identified by plotting data or when they are several standard deviations away from the mean.

Poverty line – The threshold of cost of living, below which a person or household is considered poor.

Public-private initiatives – Collaboration between public bodies such as local or central government and other state-owned entities and the private sector mainly aimed at delivering public services.

Pre-payment meter – Meters that allow customers to pay for service in advance, with payment balances decreasing as electricity is used. Most meters have illustrated and labeled display units that show the amount of electricity available. Electricity units are credited with the help of codes that correspond to meter number and amount of electricity or magnetic strips.

Pumped storage hydro-electric scheme - Power storage facilities used to generate electricity. Water is pumped up into a reservoir, when electricity load on the system is low and during times of peak, the water is released to drive a turbine and generate electricity.

Single rate tariff: A tariff that has no fixed charge and whose cost of electricity per month is directly proportional to the consumption per month.

Short Run Marginal Costs (SRMC) - Incremental costs of operating and maintaining a power system based on current costs and ignoring costs of future investment.

Transformer- An electrical unit that converts one level of electricity to a desirable level through electromagnetic induction. For example from low-voltage electricity of a generator to high voltage electricity in transmission lines and from high voltage transmission lines to very low suitable for household use.

APPENDIX 2: SUPPLY SIDE QUESTIONNAIRE

SUPPLY SIDE BENEFITS AND COSTS OF THE MBAYANI LOW COST ELECTRIFICATION PROGRAM

1. Please tell me your name and position in ESCOM?

   a) Name_____

   b) Position_____

   c) Department_____

2. Does ESCOM have a set policy on low cost connections and compact ready boards in particular? Please explain.

3. When were the compact ready board connections made?

Year	Number of connections made
2001	
2002	
2003	

4. Did ESCOM conduct a technology comparative analysis before choosing compact ready boards? If yes, what other connection options were considered for the urban poor?

5. Why did ESCOM decide to use compact ready boards in particular?

6. How many compact ready board connections have been made nationwide?

Year	Location	Number of connections	Type of board
2001			
2002			
2003			

7. What criteria did ESCOM use to identify who to connect using compact ready boards?

8. Was there any demand side needs assessment survey prior to the implementation of the Mbayani low cost connection program? Please explain

9. Was there a cost-benefit analysis study prior to the compact ready boards low cost electrification program? Please explain.

10. How much did each compact ready board connection cost the utility in the year 2000? (Hardware and labour costs)

11. How much did users of compact ready boards pay for the connection in 2000?

12. What was the tariff for consumers with compact ready boards connections?

Year	Tariff per month
2001	
2002	
2003	

13. What criteria were used to set the compact ready board tariffs? Please explain.

14. How are the compact ready board costs recovered?

Recovery	Percentage of cost	Amount
Tariff		
Connection charge		
Subsidy		
Others (Please specify)		

15. What has been the rate of recovery per annum of the cost of ready board connection and what percentage of the costs incurred has already been recovered?

16. How much did one conventional connection cost in the years 2001?

Year	Cost of convention connection
2001	

17. How much did users of conventional connections pay for the connection in the following years in Mbayani on average?

Year	Cost of convention connection
2001	
2002	
2003	

18. What tariff structure did ESCOM charge domestic users with compact ready boards in Mbayani in…

Year	Tariff per month
2001	
2002	
2003	

19. How was the convection (meter) tariff decided upon?

20. How are conventional connections costs recovered?

Recovery	Percentage of cost per year per customer	Amount
Tariff		
Connection charge		
Subsidy		
Others (Please specify)		

21. Please provide cost details of connection in Mbayani in year 2001 as below

Item	Expenditure (MK)	
	Compact	**Conventional**
Lines		
Line equipment (Including fuses and switches)		
Substations (Including ground mounted equipment and gear)		
Transformers (Including power and distribution transformers)		
Grounding (Including Pole-mounted equipment and substation grounding)		
Meters/Compact ready boards)		
Others (Specify)		
Total		

22. Please tell us your opinion of compact ready boards in terms of costs to the utility

23. Please tell us your opinion of compact ready boards in terms of benefits to the utility

24. How do the consumption patterns of ready board users in Mbayani compare to those of conventional metered connection? Please explain.

25. What has been, in your opinion, the major challenge of compact ready boards connections

26. How do you rate the understanding of users of compact ready boards?

APPENDIX 3: DEMAND SIDE QUESTIONNAIRE

ELECTRICITY USE, COSTS AND BENEFITS IN COMPACT BOARDS CONNECTED AREAS

Name of Interviewer:
Date of Interview:
Time of Interview:
Checked by:

Note to enumerator: Remember to explain the objective of the study. The objective of this study, undertaken by a student at the University of Cape Town is to learn more about how households connected using compact ready boards use, pay and benefit from the connection and the problems the face.

Make sure the interviewee lives in that households and is either a household head, a partner of the household head or a house member who is over 21 years of age and can articulate household issues well.

Explain to the interviewee to answer for the entire household not only for himself or herself.

Explain that the information is confidential, will be used for academic purposes only and will not be communicated to other people in the community.

Remember to take note of any interesting explanations, suggestions and discussion that may result from the interview.

Do not attempt to answer questions whose answers you are not sure about or make promises that you will not fulfil. Explain why you may not answer such questions and if appropriate suggest to the interviewee to approach relevant authorities such as ESCOM.

Remember to thank interviewees for their participation and time.

I. Household type, head and respondent

1. Please tell us your name and surname? _____
2. What is the respondent's position in the household? _____
3. Who is the head of the household? _____
4. What is the status of your house ownership? ___(Please tick appropriate space below)__

Rented_____ Owned_____ Being bought_____

5. How many people live in the house? _____

II. Electrification

6. When did you receive electricity in your home? _____
7. Did you attend the launching meeting? Yes [ ] No [ ]
8. Did you understand what the connection offered? Yes [ ] No [ ]

Please explain

_____

_____

_____

_____

9. Did you understand what you were supposed to pay? How much were you told to pay? Yes [ ] No [ ] If "No" Please explain what you don't understand.

_____

_____

_____

10. How much do you pay per month now?

_____

_____

_____

11. How do you compare the ease of paying for electricity with the ease of buying fuels such as paraffin, charcoal and firewood. Please explain.

12. How would you compare the ease of paying for electricity using the tariff used here to the ease of paying for electricity depending on your consumption as households with metered electricity do? Please explain.

(Enumerator: Please remember to explain about metered electricity)

III. Fuel Usage and Electrification Benefits

13. What did you use for the following before electrification?

Code	Activity	Fuel choice (s)	How often
13a	Lighting		
13b	Cooking		
13c	Ironing		
13d	Radio		
13e	Television (TV)		
13f	Refrigeration		
13g	Water heating		
13h	House cooling		

14. What do you use for the following now (after electrification)

Code	Activity	Fuel choice (s)	How often
14a	Lighting		
14b	Cooking		
14c	Ironing		
14d	Radio		
14e	Television (TV)		
14f	Refrigeration		
14g	Water heating		
14h	House cooling		

15. Why don't you use electricity for ....

Code	Activity	Reason for not using electricity
15a	Lighting	
15b	Cooking	
15c	Ironing	
15d	Radio	
15e	Television (TV)	
15f	Refrigeration	
14g	Water heating	
14h	House cooling	
14i	Others (specify)	

16. What electrical appliances do you have?

Code	Appliance	Ownership (Mark with a tick if household possesses the appliance
16a	Hotplate (Specify number of plates)	
16b	Stove	
16c	Iron (specify whether dry or steam)	
16d	Radio	
16e	Television (TV)	
16f	Refrigerator	
16g	Water Boiler	
16h	Fan	
16i	Others (Please specify)	

17. Has your household benefited from the connection? Yes [ ] No [ ]

18. What are the ways in which your household has benefited from the electrification program connection? Please rank the benefits of electricity in the order in which you perceive to be most useful to you.

Service benefit	Rank according to benefit

19. Please elaborate on the benefits mentioned in Question 18.

IV. Household Income and Expenditure

20. How much did the following fuels cost you per month before the electrification?

Code	Fuel Type	Amount of fuel per month	Cost in MK
17a	Firewood		
17b	Charcoal		
17c	Paraffin		
17d	Dry Cells		
17e	Electricity		
17f	Car Batteries		
17g	Other (Specify)		
	Total (Do not fill in this row)		

21. How much do the following fuels cost you per month now (after electrification)?

Code	Fuel Type	Amount of fuel per month	Cost in MK
18a	Firewood		
18b	Charcoal		
18c	Paraffin		
18d	Dry Cells		
18e	Electricity		
18f	Car Batteries		
18g	Other (Specify)		
	Total (Do not fill in this row)		

22. What was your monthly expenditure/bill on the following before electrification?

Code	Expense Item	Monthly Cost
19a	Rent/Mortgage	
19b	Food	
19c	Water	
19d	Health	
19e	School fees	
19f	Transport	
19g	Other (Specify)	
	Total (Do not fill in this row)	

23. What is your monthly expenditure/bill on the following now (after electrification)?

Code	Item	Monthly Cost
20a	Rent/Mortgage	
20b	Food	
20c	Water	
20d	Health	
20e	School fees	
20f	Transport	
20g	Other (Specify)	
	Total (Do not fill in this row)	

24. How many of the people living here contribute to household expenses?

Person	Contribution	Frequency
E.g. Daughter	Groceries or cash (specify Amount)	Weekly/monthly etc

25. What are your main sources of income?

Source	Amount	Frequency
Salary		
Rentals		
Business(Specify nature of business)		
Gifts/Remittances		
Other (Please specify)		

26. Describe the business that you undertake. Please specify whether it is home based or not.

27. Did the business start as a direct result of electrification? Yes [ ] No [ ]

28. How has the business benefited from the electrification? Please explain.

29. Please tell us anything relating to benefits and cost of electricity, which you feel you did not have the chance to explain or clarify any other matter relating to the survey?

Note to enumerator: Please remember to thank the respondent for participating in the survey.

UNIVERSITY OF CAPE TOWN
Department of Mechanical Engineering
Rondebosch, Cape Town, South Africa

THE EFFECT OF STAND-OFF DISTANCE ON THE FAILURE OF THIN PLATES SUBJECTED TO BLAST LOADS

Neville Jacob

2005

Submitted to the University of Cape Town in partial fulfillment of the degree of MSc in Mechanical Engineering

Declaration

I, Neville Jacob, declare that this dissertation is essentially my own work. It is being submitted in partial fulfillment of the requirements for the Masters of Science in Engineering degree at the University of Cape Town and has not been submitted in this or any other form for a degree at any other university.

Neville Jacob
August 2005

Abstract

This investigation examines the effect of stand-off distance on the response of fully clamped circular plates subjected to blast loads.

The experimental procedure consists of creating a blast load using disc shaped plastic explosive mounted onto a tube of required length. The length of the tube is the stand-off distance. Different lengths of tubes are used ranging from 25mm to 300mm. The internal diameter of the tube is 106mm. The dimension of the circular test plate is governed by the internal diameter of the tube. Hence all tests are conducted on 106mm diameter circular plates of thickness 1.9mm. The test plate is clamped between two clamping plates. The tube is screwed onto one of the clamping plates.

The plate responses range from large inelastic deformation to complete tearing at the plate boundary. The deformed plate profile is dependent on stand-off distance. For stand-off distances ranging from 13mm to 40mm an inner dome atop a larger global dome is observed. In the case of stand-off distances ranging from 50mm to 300mm the deformed plate profile resembles a large global dome.

The results show that mid-point deflection decreases with increasing stand-off distance for a given charge mass. The mid-point deflection drops rapidly from stand-off distance of 13mm to 50mm, from stand-off distance of 75mm to 300mm the mid-point deflection asymptotes with similar values measured for a given charge mass. The results show two distinct loading regimes that occur depending on the stand-off distance between the explosive charge and the plate. At stand-off distances less than the plate radius of 53mm (13mm to 40mm), the blast load is considered to be focused. This type of loading is referred to as localised loading. For stand-off distances greater than the plate radius (100mm to 300mm), the loading is said to be uniformly distributed over the entire plate area. At stand-off distances of 50mm to 75mm, the plate deformations exhibit a transition phase from localised loading to uniform loading.

Theoretical and empirical analysis using Jones damage number, Nurick and Martin damage number and strain energy analysis to predict mid-point deflection of the deformed plate is performed. Appropriate modifications are made to above mentioned damages numbers and strain energy analysis to account for the effect of

stand-off distance on plate deformation. The modified analyses show satisfactory correlation with experimental results.

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Notation

A	Plate area ($A = \pi(D/2)^2$)
A_0	Loaded area
B	Plate half width
D	Plate diameter
H	Plate thickness
I	Impulse
L	Plate half length
M_0	$\sigma_0 H^2/4$
P_s	Peak overpressure
R	Plate radius
R_0	Charge radius
S	Stand-off distance
v_{det}	Detonation velocity
V_0	Initial velocity
U_{def}	Deformation strain energy
U	shock velocity
u	Particle velocity
$U_{rarefaction}$	Rarefaction velocity
Z	Scaled distance
b	Plate width (2B)
h	Charge height
l	Plate length (2L)
α	Johnson damage number
λ	Jones dimensionless number
Φ_q	Nurick dimensionless number (quadrangular plates)
Φ_c	Nurick dimensionless number (circular plates)
ζ_c	Loading parameter (circular plates)
ζ_{ql}	Loading parameter (quadrangular plates)
μ	Mass per unit area (ρH)
β	Aspect ratio
δ	Mid point deflection
ρ	Material density
σ_0	Static yield stress of material
σ_0^1	Dynamic yield stress of material

Acknowledgement

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Last but not least my parents Mr. and Mrs. Jacob and my sister Clarine, who have always been supportive and given much encouragement.

1 Introduction

Investigations into the failure of thin plates subjected to impulsive loads have been going on for some years as reported by Nurick and Martin [1, 2]. Understanding the way plates fail under blast loading lends itself to improved designs capable of resisting blast damage.

Previous experimental work at the University of Cape Town has concentrated on uniform and localised loading of mild steel plates at a given stand-off distance between the explosive and test plate in order to investigate plate geometry, tearing at the boundary [3, 4, 5] and in the central area of the plate [6, 7, 8], different boundary fixations [3, 9] and the effect of plate thickness [7, 8].

Other experimental works include the study into structural response of plates subjected to air pressure generated from explosive devices. Jacinto et al [10] report experiments conducted using two quadrangular un-stiffened plates with different boundary conditions (one clamped in the soil and another clamped along the four edges). The experiments were carried out to validate numerical modelling. The effect of explosive stand-off distance on square plates is reported by Akus and Yildirim [11]. The test were carried out using C4 plastic explosives of different masses (131g to 654.8g) at stand-off distances ranging from 200mm to 600mm.

This thesis reports on the results of experimental investigation into the inelastic response of circular plates subjected to blast loads at various stand-off distances.

The purpose of this investigation is to ascertain the influence of stand-off distance between the explosive and a fully clamped circular plate mounted on a ballistic pendulum. The response of the circular plate is described by its deflection resulting from the blast load applied by the explosive.

In the experiments described in this report, the stand-off distance is varied using 106mm internal diameter mild steel tubes of different lengths. A tube of required stand-off distance is screwed onto a clamping plate. The test plate is sandwiched between the tube and a second clamping plate. The explosive mounted on a polystyrene pad is placed at the open end of the tube. The test rig is then attached

onto a ballistic pendulum. The impulse applied by the explosive on the test plate is measured from the oscillation of the ballistic pendulum. The final mid-point deflection of the plate is measured using a digital height gauge.

The objectives of this thesis are to:

- Investigate the effect of different stand off distances between the explosive and test plate.
- Compare experimental results with previously reported analytical and empirical relations developed to predict mid-point deflection of plates subjected to blast loads.
- Incorporate appropriate modifications to analytical and empirical relations if required.
- Investigate the effect of polystyrene on plate deformation and applied impulse.
- Draw conclusions and recommendations based on the findings.

The scope of the investigation was limited to 1.9mm thick circular plates of diameter 106mm subjected to blast loading using explosive charge of diameter 34mm.

The thesis is based on experiments conducted in the blast laboratory of the Blast Impact and Survivability Research Unit (**BISRU**) at the University of Cape Town.

Chapter 2 details a literature review that covers background into blast loading, theoretical work and experimental results. Past experimental results are used for comparison with results from this investigation.
The experimental details are described in Chapter 3, along with material properties of mild steel plates used in the experiments.
Experimental observations are described in Chapter 4, including tables containing the experimental data recorded from the tests.
Analysis of the experimental results is presented in Chapter 5 including graphs and results of theoretical analysis performed.
Conclusions are drawn and recommendations made based on the findings in Chapters 6 and 7 respectively.

2 Literature review

A blast load is generated by detonating explosives which interact with any objects in its path causing widespread damage and represent major disaster (Kinney [12]). The blast load is generally expressed in terms of its pressure – time history. In reality the pressure – time history of a blast event is very complex, hence simplified models are often used in numerical modelling of structures subjected to blast loads. A blast load is considered impulsive if the duration is significantly lower than the natural frequency of the structure, as reported by the Steel Construction Institute [13]. This means that the structure does not have time to fully react to the blast load.

2.1 Defining an explosion

Baker [14] defines explosion as the generation of a pressure wave of finite amplitude in air by a rapid release of energy. Hence an explosion forms a blast wave. Kinney [12], states that the source of the sudden release of energy is irrelevant, for example it could be from gun powder or wheat flour dust. However, the nature of the energy release is important. The release of energy must be sudden and an accumulation of energy must occur at the region near the source. This accumulation of energy is then rapidly dissipated in various ways; the most pertinent one is in the form of a blast wave.

2.1.1 Blast phenomena

A detonation initiated at the centre of an explosive material will result in a rapid and stable chemical reaction which propagates through the un-reacted explosive. A detonation wave is created that travels at supersonic speeds (in the order of several thousand metres per second) depending on the density of the explosive, as shown in Figure 2.1. In general the detonation velocity is higher for denser explosives. The detonation wave quickly converts the explosive material into a very hot, dense and high pressure gas. This volume of gas is the source of the subsequent strong blast waves in air. The pressures behind a detonation front vary from 10GPa to 30GPa. However, only a third of the total chemical energy available is released during the detonation process for most high explosives. The remaining two-thirds of the chemical energy are released more slowly in chemical reactions as the detonation

products mix with air and burn. This secondary release of energy has little effect on the blast wave property since it is a much slower process (TM5-1300 [15]).

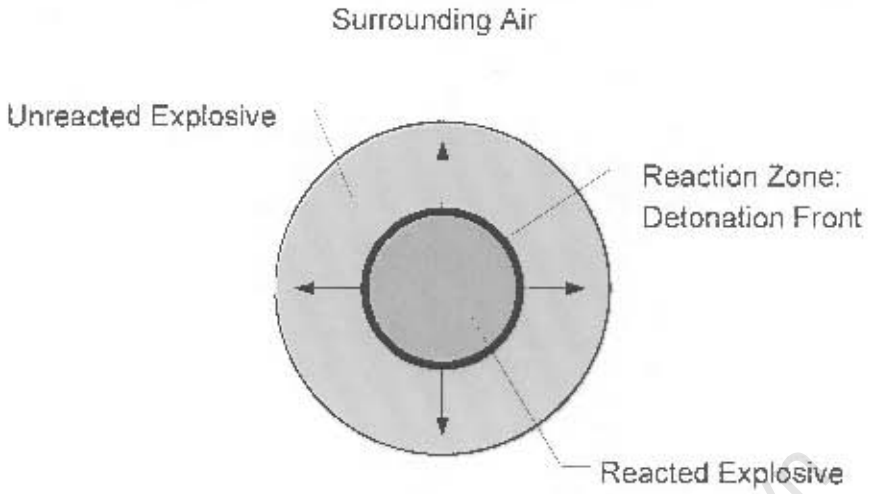


Figure 2.1: Illustration of detonation front propagating within the explosive

The blast effect of the explosion comprises a shock wave composed of a high intensity shock front created by gases from the chemical reaction during detonation. A compressed layer of air is formed in front of the expanding gases that contain most of the energy of the explosion, as shown in Figure 2.2. The shock front expands outward from the surface of the explosive into the surrounding air. This is called the blast wave. The blast wave speed is much slower than the detonation wave [15].

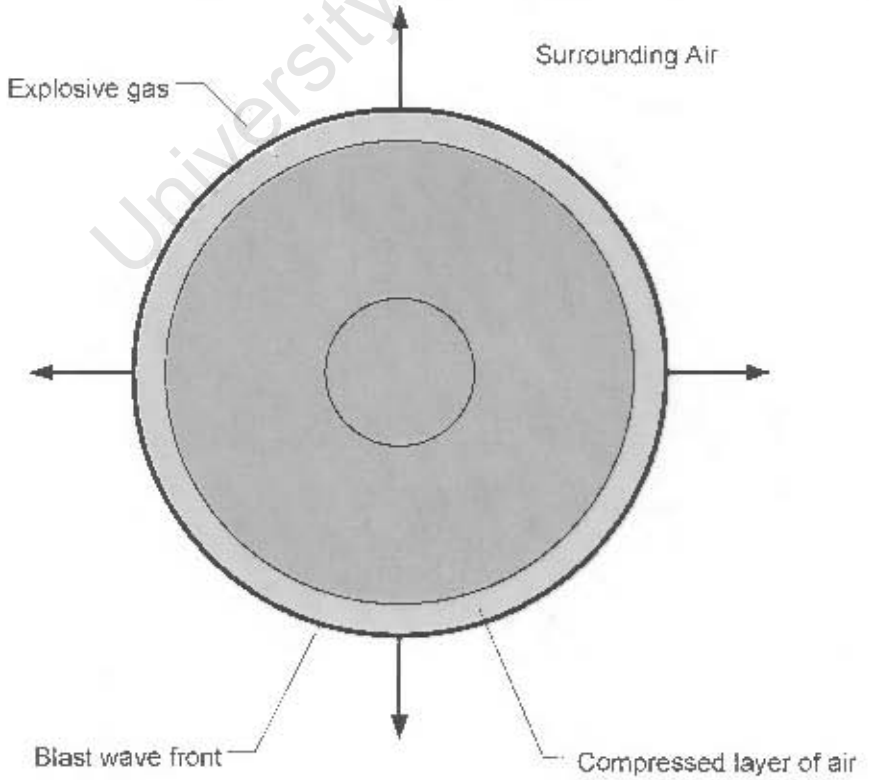


Figure 2.2: Illustration of expanding explosive gases and blast wave front

The expanding blast wave interacts with structures it comes in contact with along its path. The magnitude and distribution of the blast load is dependant on the following factors [15]:

- Explosive properties
  - Type of explosive
  - Energy output of the explosive
  - Charge mass
- Location of structure relative to the explosive charge
- Magnitude and reinforcement of blast pressure by its interaction with the structure

2.1.2 Types of explosives

Explosives are divided into two categories, namely

Initiating/Primary explosives – these are very sensitive materials that can be easily detonated by friction, spark or impact. An example of primary explosive is Lead Azide.

Lead Azide – the major initiating explosive used in most detonators and blasting caps. It is extremely sensitive to sparks, friction and impact leading to initiation of the explosive. Lead Azide has excellent storage characteristics and is stable up to almost 270°C.

Properties:

Density – 4.38gcm^{-3}

Detonation velocity – 5500ms^{-1}

Secondary explosives – these have higher energy content than initiating explosives but are stable and insensitive. Detonation is only possible through sudden and intense shock delivered using blasting caps or purpose built detonators. **TNT** and RDX are common examples of secondary explosives.

TNT – this is the most commonly produced military explosive. It is relatively insensitive to sparks, friction and impact. **TNT** requires a detonator for initiation. TNT is only slightly soluble in water, hence can be used underwater without water proofing.

Properties:

Density – 1.62gcm^{-3}

Detonation velocity – 7045ms^{-1}

RDX – this explosive is stable and less sensitive to spark, friction and impact. RDX requires a detonator for initiation. It is only slightly soluble in water and is non-hygroscopic.

Properties:

Density – 1.767gcm^{-3}

Detonation velocity – 8639ms^{-1}

2.1.3 Detonation

Rinehart and Pearson [16] describe detonation as the decomposition of explosive material into hot gases. The detonation front travels through the unused part of the explosive at speeds of the order of several thousands of metres per second leaving in its wake gases at high temperature and pressure.

In an ideal case detonation can be viewed as a sharp discontinuity travelling through an explosive at a constant velocity, referred to as the detonation velocity (v_{det}) as shown in Figure 2.3.

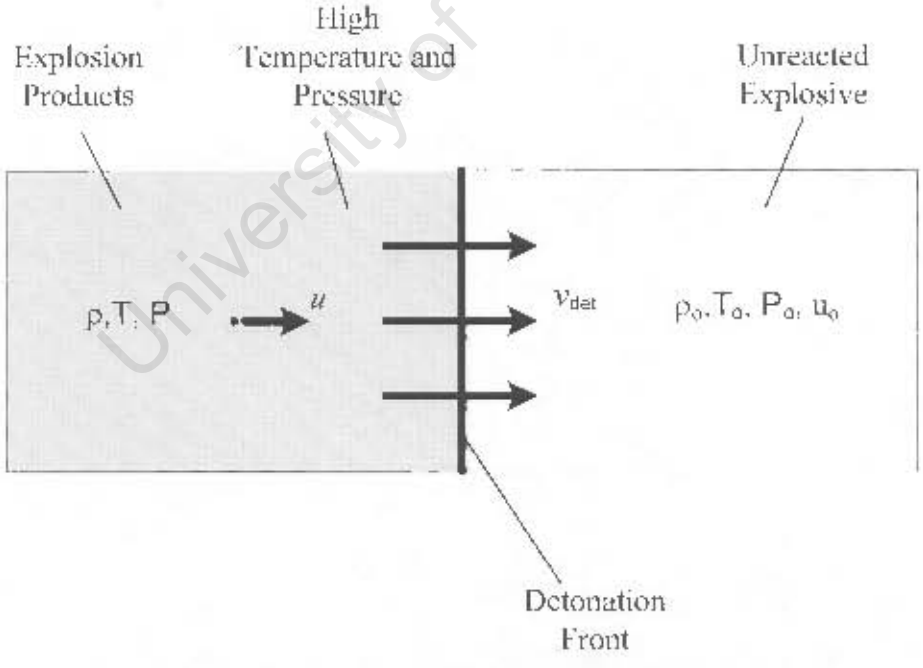


Figure 2.3: Idealised Detonation Process Parameters [16]

The initial condition of the explosive is shown in Figure 2.3 in front of the detonation front, characterised by its density ρ_o and temperature T_o. The explosive is assumed to be completely reacted behind the detonation front. The hot gases that are released from the explosive reaction fill the volume behind the detonation front at high

temperature, T, and high pressure, P, compressing the hot gases to density, ρ, that is higher than the initial explosive density (ρ_0) of the unreacted part of the explosive ahead of the detonation front and imparting a particle streaming velocity of u towards the unreacted part of the explosive.

2.1.4 Reaction zone

In section 2.1.3, it is assumed that conversion of the solid explosive to gaseous products happens instantaneously during detonation. In reality, this is not feasible as all chemical reactions occur over a finite time. Therefore the boundary between the reacted and unreacted parts of the explosive is not sharp but rather of finite thickness, as shown in Figure 2.4.

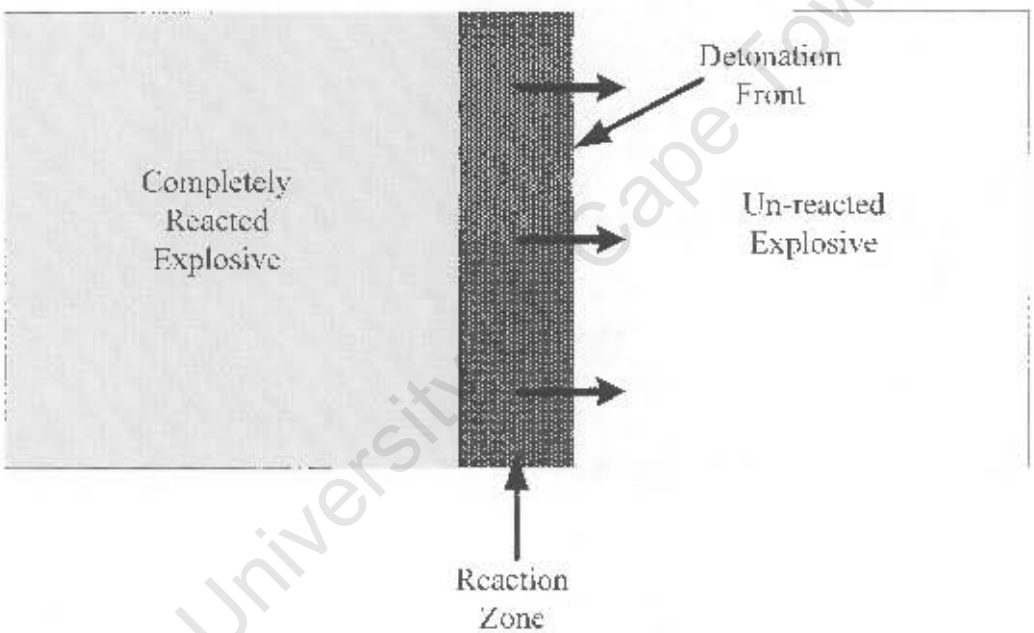


Figure 2.4: Schematic view of the reaction zone in an explosive [16]

The size of the reaction zone has an important influence on the geometry of the explosive charge. In unconfined explosive charges the gaseous products can expand laterally and literally blow away un-reacted explosive before the completion of the reaction. In the case of very thin sheet or elongated cylinder (charge length much greater than charge diameter) shaped explosive as shown in Figure 2.5 (a) and (b), this could result in incomplete detonation due to dissipation of energy due to mechanical dispersion of un-reacted explosive, [16].

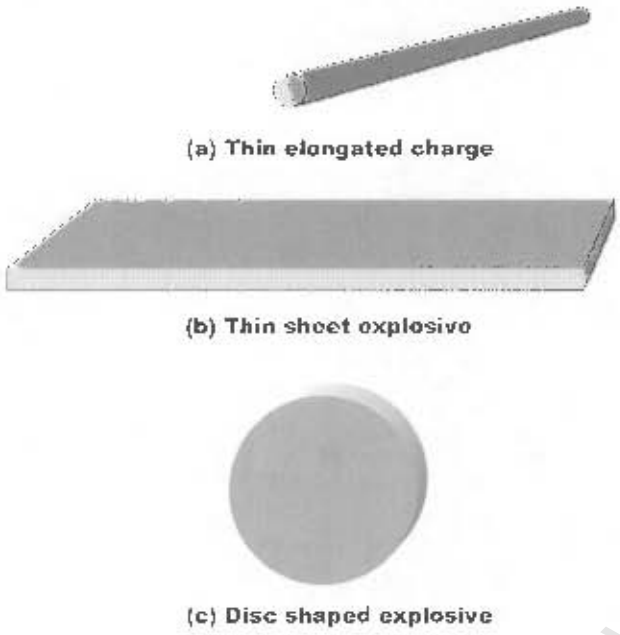


Figure 2.5: Illustration of elongated cylindrical, thin sheet and disc shaped explosive

The combination of reaction zone size and mechanical dispersion of un-reacted explosive contribute to the choice of charge geometry. In the case of disc shaped explosive (charge diameter is greater than charge height) as shown in Figure 2.5 (c), detonated at the centre of the charge diameter, the explosive thickness (charge height) must be larger than the size of the reaction zone for that particular explosive.

2.1.5 Shock waves

The shock front of a blast wave is described by Cooper and Kurowski [17] as a high pressure disturbance travelling through a material. The disturbance is not smooth but discontinuous as shown in Figure 2.6. The shock pressure can stress a structure beyond its elastic limit thus deforming it permanently.

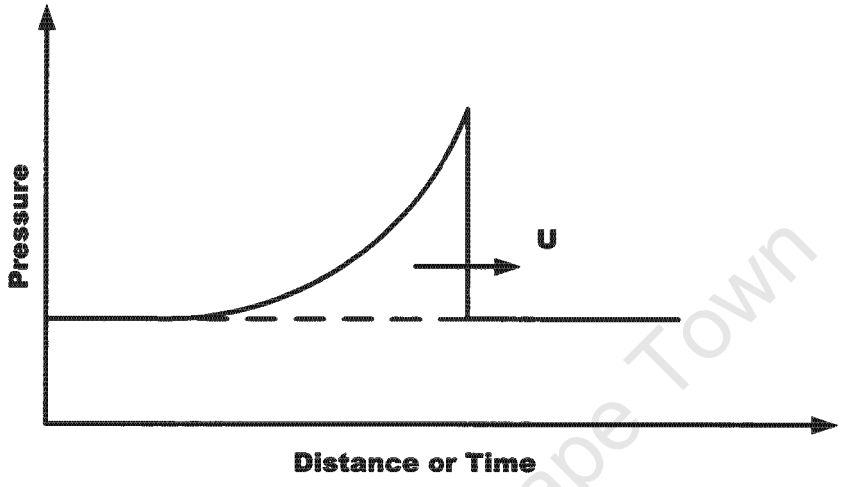


Figure 2.6: Structure of shock wave [17]

2.1.5.1 Rankine-Hugoniot jump equations for shock waves

As the shock front travels through a material, the mass, momentum and energy are conserved across the shock front. This implies that neither energy nor mass is created or destroyed by the shock process. The motion of the particles in front of the shock is due to the particles bumping into them from just behind the shock.

The conservation of mass, momentum and energy leads to three equations which describe the shock process referred to as *Rankine-Hugoniot Jump Equations*, [17].

Conservation of mass:

$$\frac{\rho_1}{\rho_o} = \frac{U - u_o}{U - u_1} \qquad \text{(eq. 2.1)}$$

Conservation of momentum:

$$P_1 - P_o = \rho_o (u_1 - u_o)(U - u_o) \qquad \text{(eq. 2.2)}$$

Conservation of energy:

$$e_1 - e_o = \frac{P_1 u_1 - P_o u_o}{\rho_o (U - u_o)} - \frac{1}{2}\left(u_1^2 - u_o^2\right) \qquad \text{(eq. 2.3)}$$

Where, P – shock pressure (GPa), U – shock velocity (km/s), u – particle velocity (km/s), ρ – density (g/cm^3), e – internal energy

Note: the subscripts 0 and 1 in the Rankine-Hugoniot jump equations refer to the un-shocked and shocked part of the material respectively.

The above expressions are further simplified if the un-shocked material is at rest and at low ambient pressure. In this case, $u_o = 0$ and the pressure of the un-shocked material is so small that it can be assumed to be zero ($P_o = 0$). Hence the equations can be rewritten as follows,

Conservation of mass:

$$\frac{\rho_1}{\rho_o} = \frac{U}{U - u_1} \qquad \text{(eq. 2.4)}$$

Conservation of momentum:

$$P_1 = \rho_o u_1 U \qquad \text{(eq. 2.5)}$$

Conservation of energy:

$$e_1 - e_o = \frac{1}{2} P_1 \left(\frac{1}{\rho_o} - \frac{1}{\rho_1} \right) \qquad \text{(eq. 2.6)}$$

2.1.5.2 Attenuation of shock waves

The shock wave not only loses energy but also the shock pressure decreases with time and distance travelled. This loss in pressure is attributed to the rarefaction wave that follows a shock wave and eventually overtakes it. A simple example is illustrated in Figure 2.7 for an assumed square-wave pulse. In this case the front of the shock wave is travelling at a velocity U, which is determined by the density, ρ_o of un-shocked region and shock pressure P. The trailing rarefaction wave is travelling through the shocked and compressed material at velocity $U_{rarefaction}$. The velocity of the rarefaction wave is determined by density ρ, pressure P and particle velocity u, of the material behind and in front of it. The rarefaction wave is travelling through shocked and compressed material with density, ρ which is higher than the density, ρ_o, through which the shock wave is travelling, thus velocity, $U_{rarefaction}$ is greater than U. As the rarefaction wave travels further into the square region, the shock wave is attenuated, and its shape changes, as shown in Figure 2.8. After this change in shape the shock front pressure starts to drop until the shock wave is transformed into sound wave. The loss in pressure results in a corresponding decrease in shock velocity.

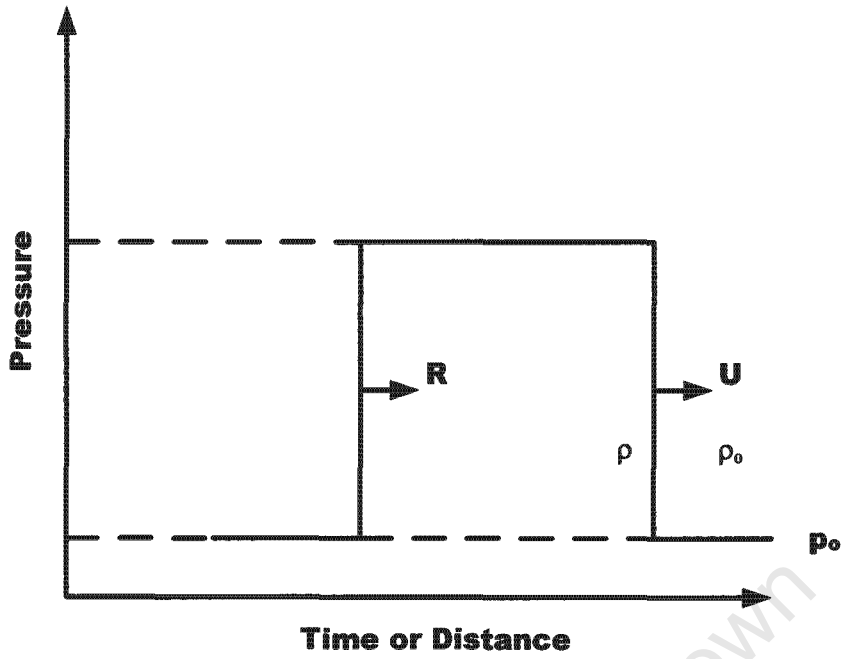


Figure 2.7: Square shock wave pulse [17]

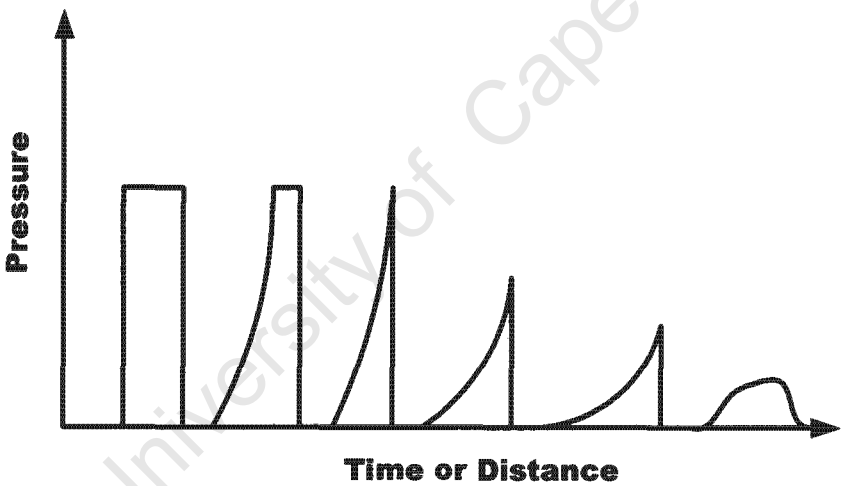


Figure 2.8: Attenuation of a square shock wave [17]

2.1.6 Detonation wave

A detonation wave is a shock wave travelling within the explosive material where the chemical reaction is carried out in the shock front. The chemical reaction continuously adds energy to the shock and compensates for energy losses. The detonation wave achieves a constant velocity v_{det}, when the energy added to the detonation wave front from the chemical reaction is in equilibrium with the energy lost through work and expansion of the detonation product gases. This is referred to as steady state detonation, (Cooper and Kurowski [17]).

A steady state detonation wave does not attenuate and retains its structure until the entire explosive is consumed. A graphical representation of the structure of the detonation wave is shown in Figure 2.9. The front of the wave is travelling at detonation velocity, v_{det}. The explosive reaction is initiated by the spike at the front end of the detonation wave, called the *Von Neuman spike* as shown in Figure 2.9. The chemical reaction of the explosion process occurs in the reaction zone immediately behind the wave front. The end of the reaction zone is called the Chapman-Jouget (C-J) plane. The pressure, density, particle and shock velocity within the C-J plane is characteristic of the particular explosive material at a given initial unreacted density. Behind the C-J plane the product gases from the chemical reactions expand. However the expansion is governed by the boundary conditions surrounding the explosive. The coupling of the energy from the explosion into another material (for example, air) occurs during this gas expansion. A decrease in pressure occurs during expansion of the hot product gases, called the Taylor wave [17].

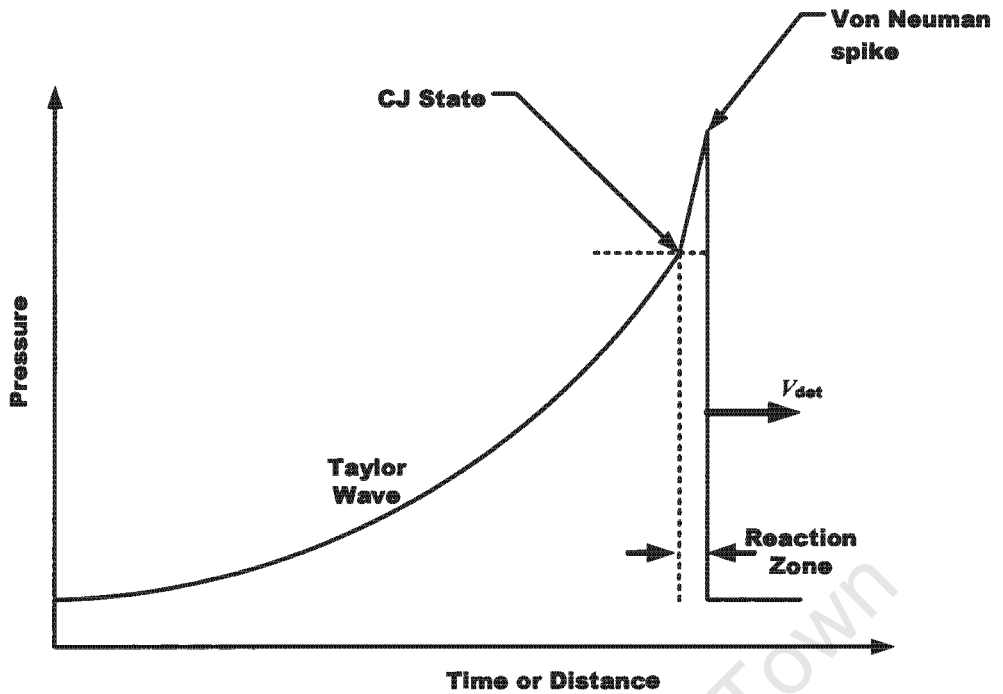


Figure 2.9: Structure of a detonation wave [17]

2.1.6.1 *Rankine-Hugoniot jump equations for detonation waves*

The Rankine-Hugoniot jump equations for shockwaves (as described in Section 2.1.5.1) apply across the detonation front. However in this case the shock pressure is replaced by the C-J pressure, P_{cj}, the shock particle velocity by u_{cj}, the shock density by ρ_{cj}, and the shock velocity by the detonation velocity, v_{det}, [17].

Mass balance:

$$\frac{\rho_{cj}}{\rho_o} = \frac{v_{det}}{v_{det} - u_{cj}} \qquad \text{(eq. 2.7)}$$

Momentum balance:

$$p_{cj} = \rho_o u_{cj} v_{det} \qquad \text{(eq. 2.8)}$$

Where, P_{cj} – C-J pressure (GPa), v_{det} – detonation velocity (km/s), u_{cj} – particle velocity at the C-J state (km/s), ρ_o – density of unreacted explosive (g/cm^3), ρ_{cj} – density in the C-J state (g/cm^3)

An approximation for determining the C-J pressure is obtained from the simplification of the momentum equation (2.8). Equation (2.9) predicts the C-J pressure for a particular explosive within an accuracy of 7% for most explosives, [17].

$$p_{cj} = \rho_o \, v_{det}^2 / 4 \qquad \text{(eq. 2.9)}$$

2.2 Blast wave phenomena

Smith and Hetherington [18] describe the blast wave phenomena as a sequence of events that follow the initiation of an explosive. The rapid release of energy from the detonation converts an explosive charge into very high pressure gas (10 – 30GPa) at very high temperature (3000 – 4000°C). The gases expand violently and the surrounding air is forced out from the volume it occupies. A layer of compressed air at high pressure is formed in front of the expanding gases which contain most of the energy from the explosion. This pressure front is referred to as the blast wave as shown in Figure 2.10, [18].

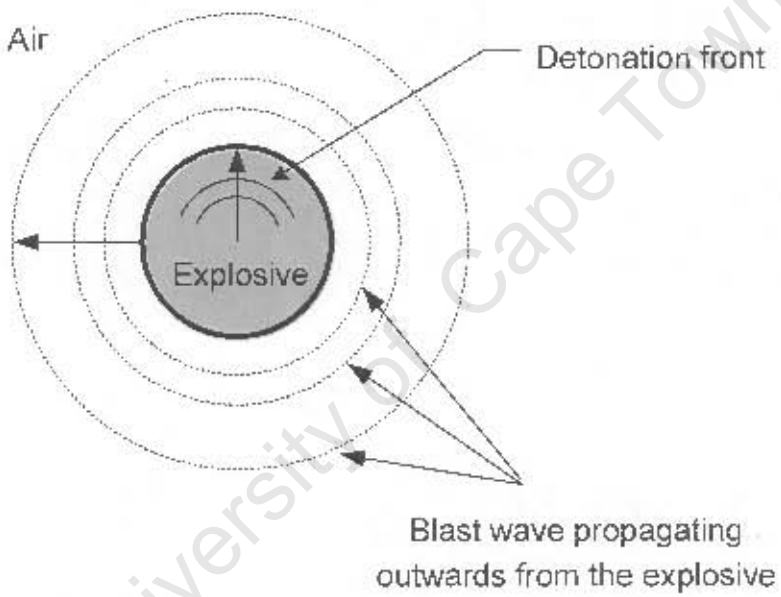


Figure 2.10: A simplified figure of detonation front propagating through an explosive and the blast wave propagating from the explosion

As the explosive gases expand the pressure drops to atmospheric pressure as the blast wave travels outwards from the source. Similarly, the pressure of the compressed air at the blast front also falls with increasing distance. As the explosive gases expand they cool and their pressure drops slightly below ambient pressure. This is because the gas molecules have mass and are moving. It takes some time and further distance of travel before their momentum is zero. The gases are now 'over-expanded' and the result is a reversal of flow towards the source driven by the small pressure differential between atmospheric conditions and the pressure of the gases. This drop in pressure is referred to as the under pressure [18].

2.2.1 Blast loading categories

The description of different blast loads described in this section is a summary of discussion in TM5-1300 [15].
Blast loads can be classified into two categories.

2.2.1.1 Unconfined explosions

This type of blast loading occurs above the surface of the ground, either in free air (free air blast), a certain distance above the ground (air burst) or a surface blast (explosive placed on the ground).

- ***Free air blast*** – In this case, the explosive is detonated in air sufficiently away from the ground such that shock waves propagate away from the centre of the explosive and arrives at the target without intermediate amplification of the wave as shown in Figure 2.11.

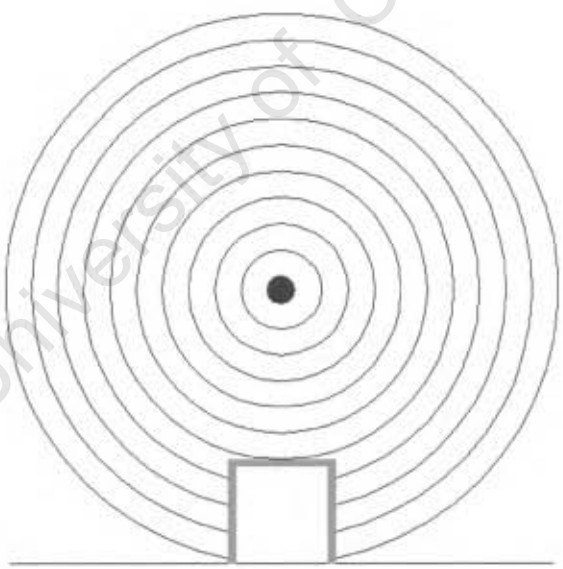


Figure 2.11: Schematic of free air blast

Above ground – in this case, the explosive is placed at a predetermined distance above the ground such that the shock wave is reflected off the ground before arriving at the target as shown in Figure 2.12.

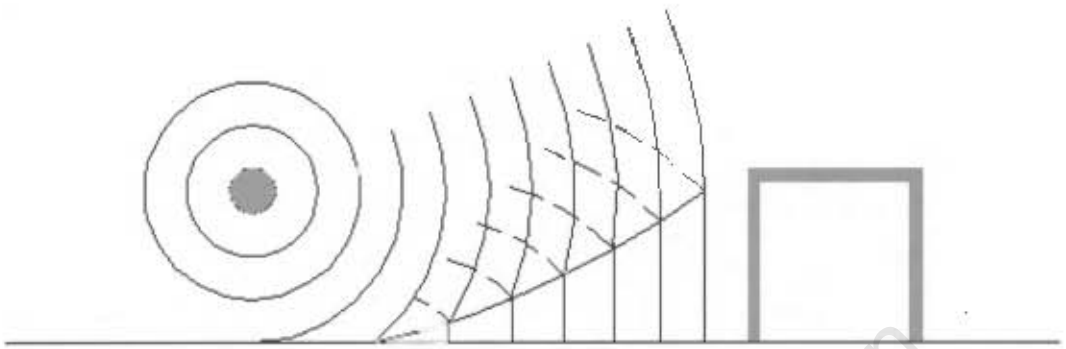


Figure 2.12: Schematic of above ground blast

- ***Surface blast*** – in this case, the explosive is placed near or on the ground. When detonation is initiated the subsequent shock wave moves from the centre of the explosive and is amplified by ground reflections, as shown in Figure 2.13.

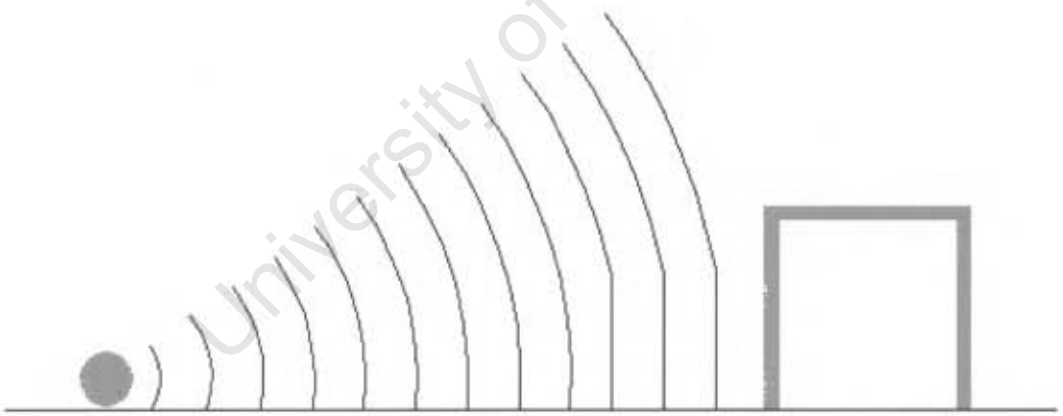


Figure 2.13: Schematic of surface blast

2.2.1.2 *Confined explosions*

This type of blast loading occurs in cases where the explosive is placed in a confined space. The level of confinement is described as follows,

- ***Fully vented*** – this type of blast loading will be produced near a barrier or confinement. The resulting shock wave is amplified by the rigid surfaces of the barrier or confining structure. The products of detonation are vented completely into the open air creating a shock wave moving away from the structure. An example is a cubicle as shown in Figure 2.14.

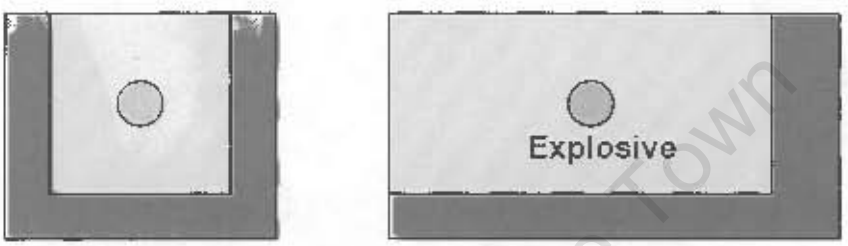


Figure 2.14: Illustration of fully vented blast loading

- ***Partially vented*** – in this type of blast loading the explosion occurs within a confining structure with limited opening to allow venting as shown in Figure 2.15. The initial shock wave is amplified by the rigid surfaces of the structure. The products of detonation are able to vent but only after a finite period of time. The confinement of detonation products results in the accumulation of high temperature and gaseous products. This is associated with a build up of gaseous pressure. This pressure has longer time duration compared to shock wave duration.

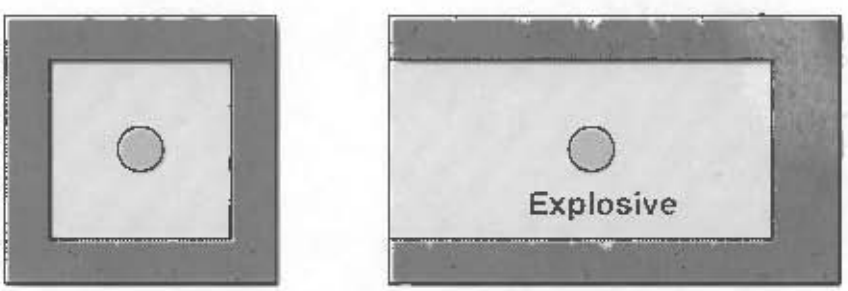


Figure 2.15: Illustration of partially vented blast loading

- ***Fully confined*** – A fully confined explosion occurs when the explosive is detonated inside a completely enclosed structure as shown in Figure 2.16. In this case the internal blast load consists of the un-vented shock wave and long duration gaseous products which is a function of the degree of confinement.

Figure 2.16: Illustration of fully confined blast loading

2.2.1.3 Effect of confinement

When an explosion is confined within a structure, the associated shock wave pressure is very high and amplified by multiple reflections within the structure. The products of detonation, (the gaseous products from the chemical reaction involved in the detonation) exert additional pressure and substantially increase the load duration. The combination of these factors leads to larger loads applied on the structure. A typical pressure-time curve for a confined explosion is shown in Figure 2.17. The initial incident and reflected blast waves are followed by several reverberating blast waves whose amplitudes are attenuated by the irreversible thermodynamic process of detonation.

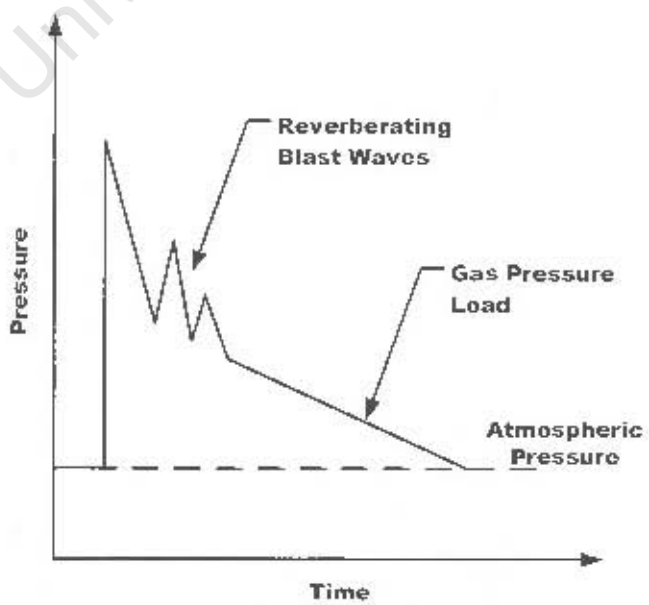


Figure 2.17: Pressure-time history for a confined explosion

2.2.2 Description of blast load

The blast load is generally expressed in terms of its pressure-time history. The specific impulse of the blast load is represented by the area under the pressure-time graph from the arrival time, t_a (as shown in Figure 2.18) is given by,

$$I_o = \int_{t_a}^{t_a+T} P(t)dt \qquad \text{(eq. 2.10)}$$

The impulse depends on the peak over-pressure, duration and the rate of decay. It is normal practice to consider the positive over-pressure only as it is larger than the under-pressure.

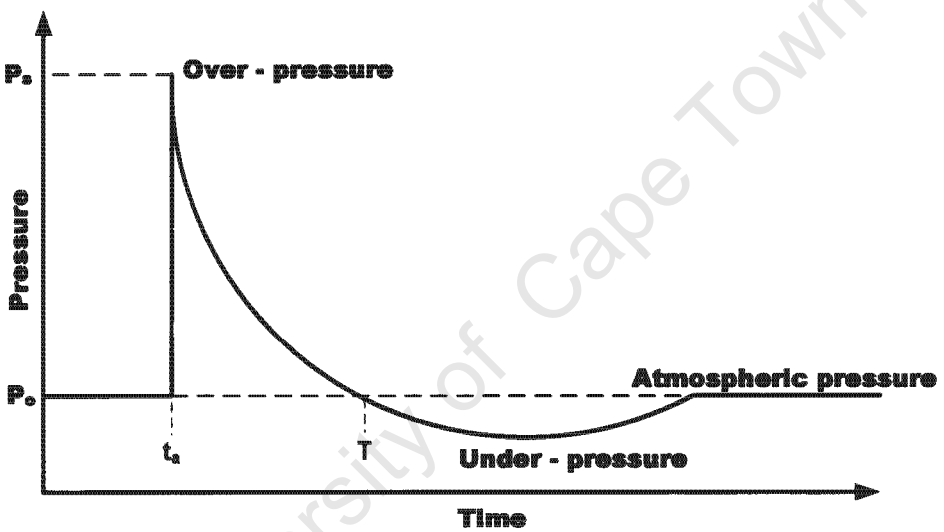


Figure 2.18: Pressure time history [13]

2.2.3 Idealised blast pressure-time history

The pressure-time history is described by exponential functions such as the Friedlander equation (eq 2.11), [14, 18].

$$P(t) = P_s\left[1 - \frac{t}{T}\right]e^{-\left(\frac{at}{T}\right)} \qquad \text{(eq. 2.11)}$$

Where, a – waveform parameter, P_s – peak overpressure, T – blast duration, t - time

However approximations of the pressure-time history are regularly used and have been found satisfactory [18] and linear decay is often used in design. In the case of conservative design approach the impulse is overestimated by assuming a pressure-time history, marked case I, in Figure 2.19. Conversely, case II, is adopted in cases

where it is desirable to preserve the impulse. It should be noted that different approximations of the pressure-time history are used other than that shown in Figure 2.18. The Steel Construction Institute [13] suggests several alternatives that are commonly used, as shown in Figure 2.20.

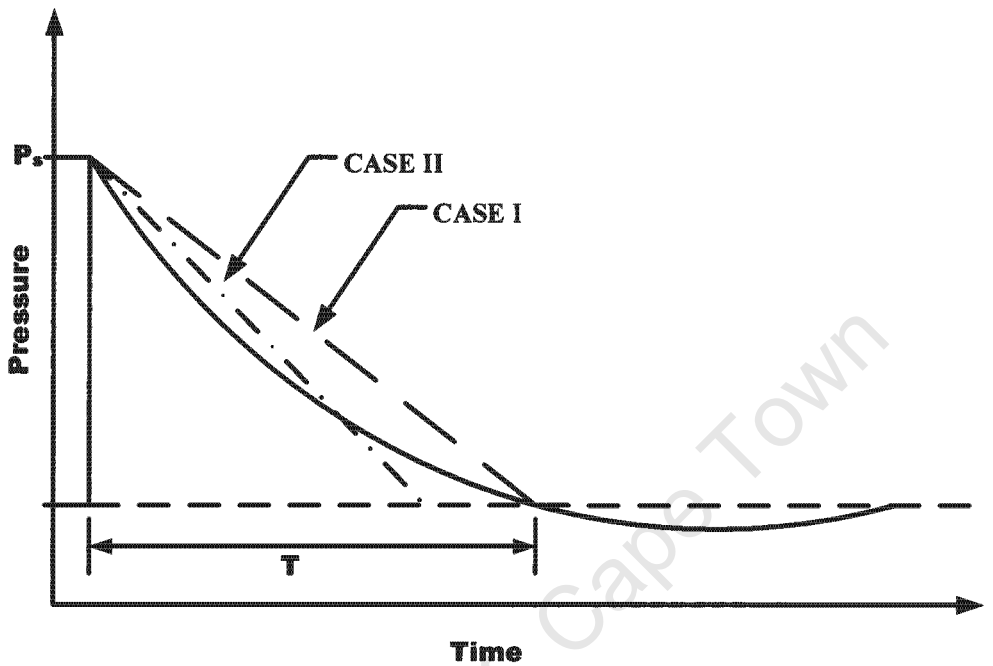


Figure 2.19: Idealization of the pressure-time history [18]

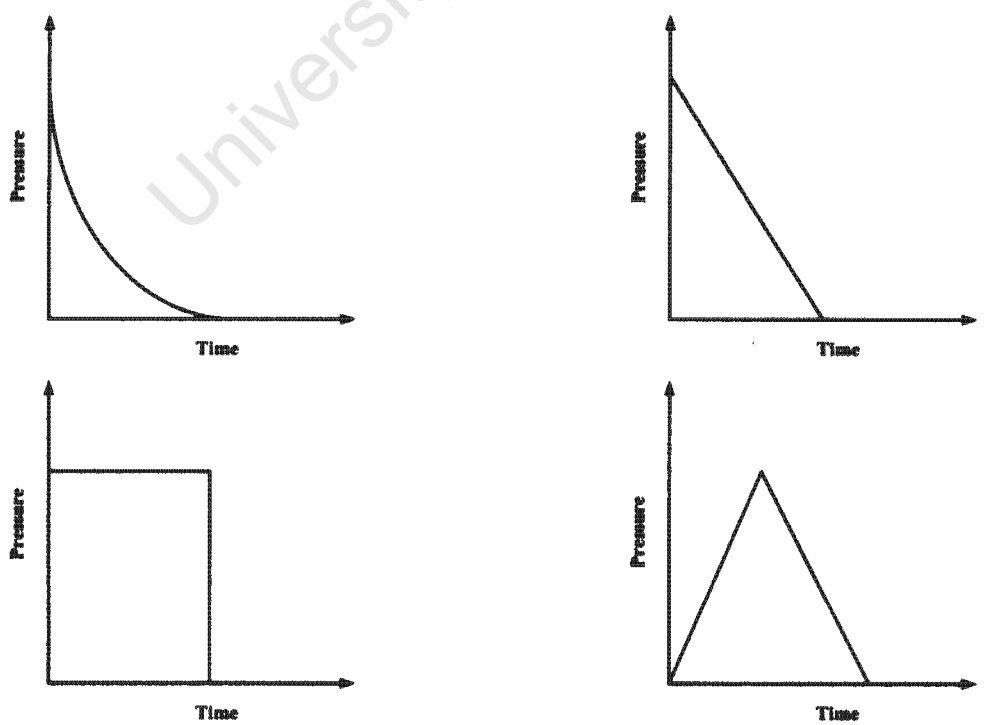


Figure 2.20: Simplified pressure – time histories [13]

2.2.4 Blast scaling

Experimental studies of large scale blast wave phenomena are expensive and difficult to perform, thus many investigators have attempted to develop models and scaling laws to describe blast wave characteristics, namely blast pressure, impulse, stand off distance and duration.

2.2.4.1 Hopkinson-Cranz scaling

The scaling law developed independently during World War I by Hopkinson and Cranz in 1915 [14, 18, 19] is the most widely known and used. The law states that "self similar blast waves are produced at identical scaled distance when two explosive charges of similar geometry and same explosive, but different size, are detonated in the same atmosphere".

The scaling law can be illustrated as follows,

Consider two charge masses W_1 and W_2 of diameter d_1 and d_2 respectively as shown in Figure 2.21.

The respective volumes of the two charges are given by

$$Volume(\text{charge1}) = \frac{\pi}{6} d_1^3 \qquad \text{(eq.2.12)}$$

$$Volume(\text{charge2}) = \frac{\pi}{6} d_2^3 \qquad \text{(eq.2.13)}$$

The charge masses W_1 is proportional to Volume (charge1) and W_2 is proportional to Volume (charge2) such that

$$W_1 \propto d_1^3 \qquad \text{(eq.2.14)}$$

$$W_2 \propto d_2^3 \qquad \text{(eq.2.15)}$$

If the charges are of the same explosive material it follows that

$$\left(\frac{d_1}{d_2}\right)^3 = \frac{W_1}{W_2} \qquad \text{(eq.2.16)}$$

$$\frac{d_1}{d_2} = \left(\frac{W_1}{W_2}\right)^{1/3} \qquad \text{(eq.2.17)}$$

The ratio of the charge diameters can be written as

$$\frac{d_1}{d_2} = \omega \qquad \text{(eq.2.18)}$$

Therefore, if the same overpressure P_s is to be produced from the two charges the ratio of the ranges at which the particular pressure is developed will also be ω. Hence the ranges at which a given overpressure is produced can be calculated from the results of equation (2.19),

$$\frac{R_1}{R_2} = \left(\frac{W_1}{W_2}\right)^{1/3} \Rightarrow \frac{R_1}{W_1^{1/3}} = \frac{R_2}{W_2^{1/3}} = Z \qquad \text{(eq.2.19)}$$

Where R_1 is the range at which a given overpressure is produced by charge W_1 and R_2 is the range at which the same overpressure is generated by charge W_2.

The Hopkinson-Cranz approach leads to the concept of scaled distance Z ($= R/W^{1/3}$). It is evident that Z is the constant of proportionality in relationships such as equations (2.17). The implication being that, an observer located at a distance R_1, from an explosive source of characteristic dimension d_1 is subjected to peak over pressure P and blast duration T. The positive blast impulse is defined by equation (2.10). The Hopkinson Scaling law then states that if an observer is positioned at a distance ZR_1 (R_2) from the centre of the explosive source of characteristic dimension Zd_1 (d_2) detonated in the same atmosphere, a blast wave of similar form with the same peak over pressure P, scaled blast duration ZT, and scaled impulse ZI is observed. All characteristic times are scaled by the same factor as the length scale factor Z. Blast peak pressure and velocities are not scaled in homologous times, (Baker [14]).

Hopkinson Scaling law applies over wide range of distance and explosive source energies.

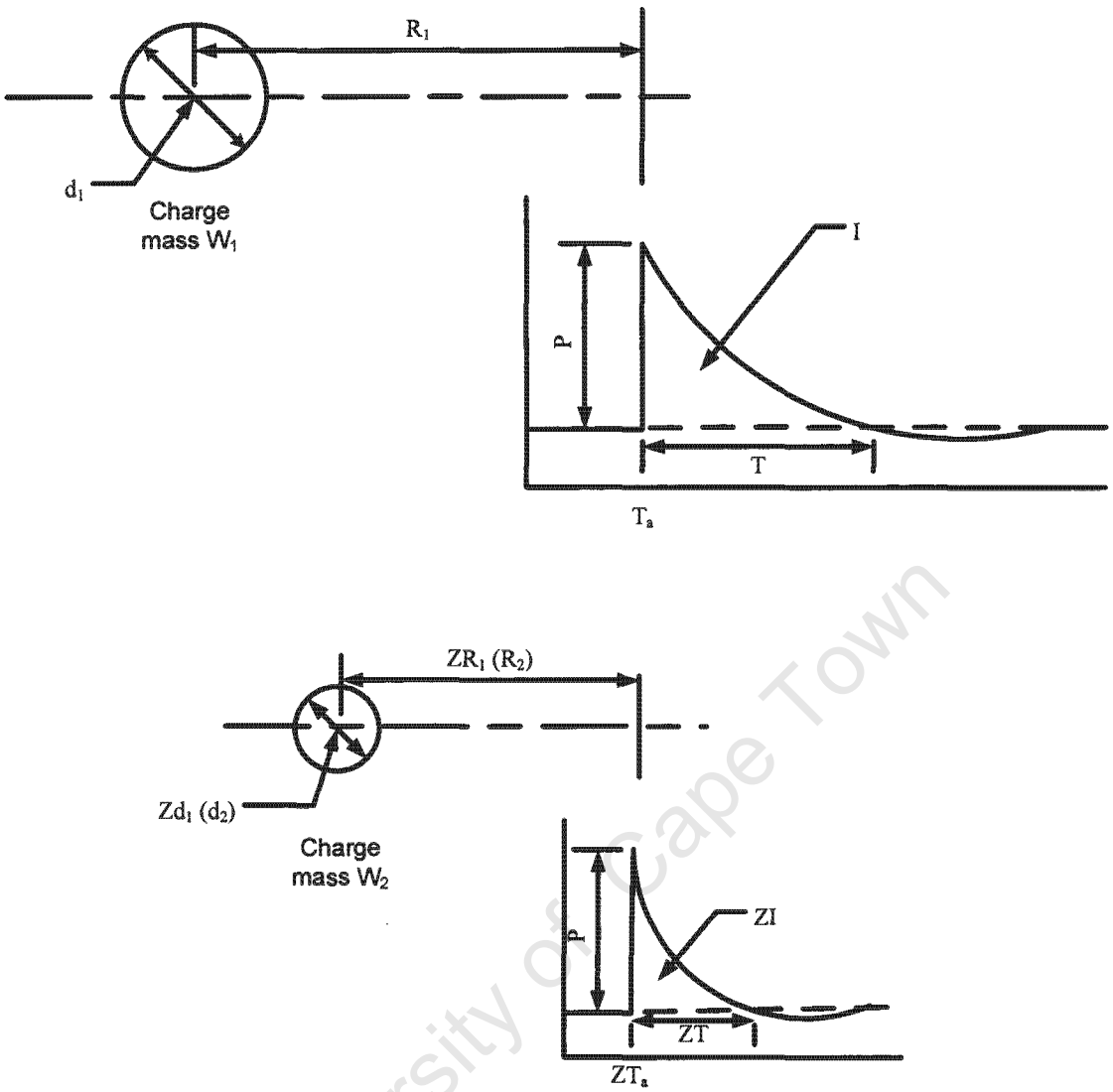


Figure 2.21: Hopkinson blast wave scaling

2.2.4.2 Sach's scaling

Another widely used scaling law was developed by Sachs [14, 19], which facilitates predictions for different ambient conditions. Sach's law states that dimensionless overpressure and impulse can be expressed as unique functions of a dimensionless scaled distance. The dimensionless parameters include quantities that include the ambient condition prior to the explosion.

2.2.5 Equations for predicting blast peak overpressure

The blast peak overpressure (P_s) and the duration of the positive pressure load (t_s) are determined as a function of scaled distance (Z) from equations developed experimentally and analytically. The analysis due to Brode [18] provides the following equations for calculating the peak overpressure, classified as near field (where P_s is greater than 10Bar) and far field (P_s between 0.1 and 10Bar).

Near Field (p_s >10 Bar)

$$P_s = \frac{6.7}{Z^3} + 1 \text{ (Bar)} \qquad \text{(eq. 2.22)}$$

Medium and Far Field (0.1<p_s<10 Bar)

$$P_s = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \text{ (Bar)} \qquad \text{(eq. 2.23)}$$

Henrych proposed three equations for blast over pressure classified according to ranges of scaled stand-off distances (Z); the equations are derived from TNT explosions [18].

For range 0.05 < Z < 0.3(m/kg$^{1/3}$)

$$P_s = \frac{14.072}{Z} + \frac{5.540}{Z^2} - \frac{0.357}{Z^3} + \frac{0.00625}{Z^4} \text{ (Bar)} \qquad \text{(eq. 2.24)}$$

For range 0.3 < Z < 1.0(m/kg$^{1/3}$)

$$P_s = \frac{6.194}{Z} - \frac{0.326}{Z^2} + \frac{2.132}{Z^3} \text{ (Bar)} \qquad \text{(eq. 2.25)}$$

For range 1 < Z < 10(m/kg$^{1/3}$)

$$P_s = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} \text{ (Bar)} \qquad \text{(eq. 2.26)}$$

Kinney and Graham proposed the equation (eq. 2.27) for peak overpressure and (eq. 2.28) for blast duration derived from the relationship between the Mach number of the shock front and ambient pressure [10].

Ratio of peak overpressure to ambient pressure

$$\frac{P_s}{P_o} = \frac{808\left(1+\left(\frac{Z}{4.5}\right)^2\right)}{\sqrt{1+\left(\frac{Z}{0.02}\right)^2}\sqrt{1+\left(\frac{Z}{0.32}\right)^2}\sqrt{1+\left(\frac{Z}{1.35}\right)^2}} \qquad \text{(eq. 2.27)}$$

Blast duration

$$\frac{t_s}{W^{1/3}} = \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^{3}\right]\left[1+\left(\frac{Z}{0.74}\right)^{6}\right]\sqrt{1+\left(\frac{Z}{6.9}\right)^{2}}} \qquad \text{(eq. 2.28)}$$

Example:

Comparing peak overpressures calculated using the equations (2.22 – 2.27).

Assume a 1kg of TNT sphere detonated at the centre. Determine the blast peak overpressure at 1m from the charge.

Scaled distance Z is given by

$$Z = \frac{R}{W^{1/3}} = \frac{1m}{(1kg)^{1/3}} = 1mkg^{-1/3}$$

Using Brode equations for Z = 1m (equations 2.22 and 2.23)

Near Field (p_s >10 Bar) (2.22)

$$P_s = \frac{6.7}{Z^3} + 1 = \frac{6.7}{1^3} + 1$$

$P_s = 7.7$ (Bar) = 0.77MPa

Medium and Far Field (0.1<p_s<10 Bar) (eq. 2.23)

$$P_s = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 = \frac{0.975}{1} + \frac{1.455}{1^2} + \frac{5.85}{1^3} - 0.019$$

$$P_s = 0.975 + 1.455 + 5.85 - 0.019$$

$P_s = 8.26$ (Bar) = 0.83MPa

Using Henrych equations for Z = 1m (equations 2.25 and 2.26)

For range 0.3 < Z < 1.0(m/kg$^{1/3}$) (eq. 2.25)

$$P_s = \frac{6.194}{Z} - \frac{0.326}{Z^2} + \frac{2.132}{Z^3} = \frac{6.194}{1} - \frac{0.326}{1^2} + \frac{2.132}{1^3}$$

$$P_s = 6.194 - 0.326 + 2.132$$

$P_s = 8$ (Bar) = 0.80MPa

For range 1 < Z < 10(m/kg$^{1/3}$) (eq. 2.26)

$$P_s = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} = \frac{0.662}{1} + \frac{4.05}{1^2} + \frac{3.288}{1^3}$$

$$P_s = 0.662 + 4.05 + 3.288$$

$P_s = 8$ (Bar) = 0.80MPa

Using Kinney and Graham equation for Z = 1m (equation 2.27)

$$\frac{P_s}{P_o} = \frac{808\left(1+\left(\frac{Z}{4.5}\right)^2\right)}{\sqrt{1+\left(\frac{Z}{0.02}\right)^2}\sqrt{1+\left(\frac{Z}{0.32}\right)^2}\sqrt{1+\left(\frac{Z}{1.35}\right)^2}} = \frac{808\left(1+\left(\frac{1}{4.5}\right)^2\right)}{\sqrt{1+\left(\frac{1}{0.02}\right)^2}\sqrt{1+\left(\frac{1}{0.32}\right)^2}\sqrt{1+\left(\frac{1}{1.35}\right)^2}}$$

$$\frac{P_s}{P_o} = 9.96$$

Where P_o – atmospheric pressure (0.101MPa)

Therefore,

$P_s = 1010$ KPa = 1.01MPa

The peak overpressure at a distance of 1m from the charge calculated using Brode's equation for near field (equation (2.22)) is lower than that determined using the equation for medium to far field (equation (2.23)). The peak overpressure obtained using equations proposed by Henrych (equations (2.25 and 2.26)) and Kinney and Graham (equation (2.27)) are similar to that determined using Brode's equation for medium and far field. The values for peak overpressure calculated using the different equations range from 0.80MPa to 1.01MPa. Hence, it is important that the correct equation is used to determine the peak overpressure. Care must also be taken to ensure that the equation is applied within its specified range of validity.

2.2.6 Blast curves

The use of scaled distance (Z) in blast curves as shown in Figure 2.22, [18], and those presented in TM-5-1300 [15] allows for a compact and convenient representation of blast wave data. It should be noted that some of these charts (as shown in Figure 2.22) are based on results from experiments using spherical charges of TNT detonated in air.

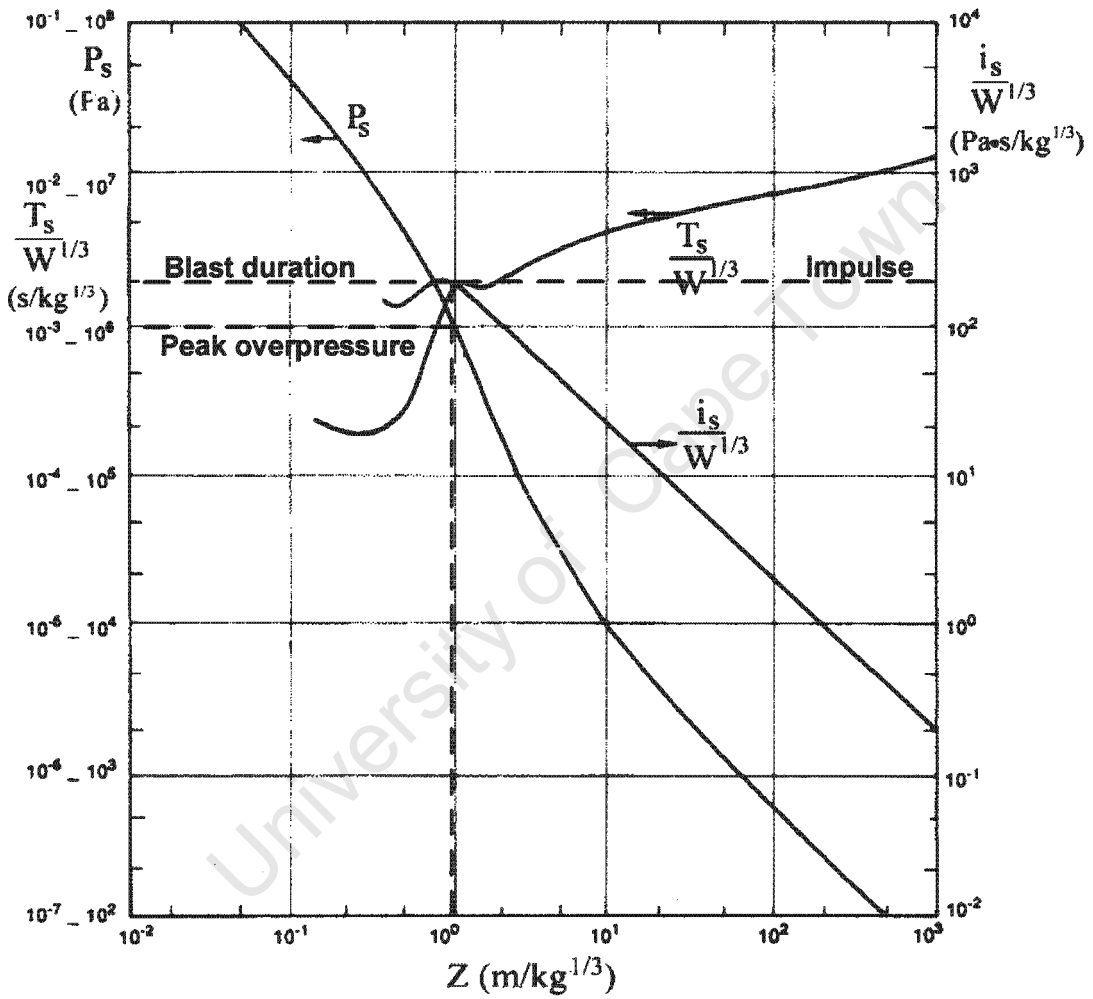


Figure 2.22: Peak overpressure (Ps) for spherical charges of TNT detonated in air [18]

An example of using blast curves is as follow,

Assume 1kg of TNT sphere detonated at the centre. Determine the blast peak overpressure, duration and impulse at a distance of 1m from the explosive.

Scaled distance Z is given by

$$Z = \frac{R}{W^{1/3}} = \frac{1m}{(1kg)^{1/3}} = 1mkg^{-1/3}$$

From the chart shown in Figure 2.22 (dashed lines are used as guides for the reader), the peak pressure, duration and impulse are interpolated,

Peak pressure – 10^6Pa = 1.00MPa,

Blast duration – 0.002sec = 2ms

Specific Impulse – 200Pa.sec

The peak overpressure magnitude determined using the blast curves is similar to that obtained using the blast overpressure equations described in Section 2.2.5.

2.2.7 Reflected pressure

When blast waves encounter a solid surface denser than air it will reflect from it. The simplest case is that of an infinitely large rigid surface onto which the blast wave impinges upon at zero angle of incidence. In this case the incident blast wave front travelling at velocity U undergoes reflection when the forward moving air molecules in the blast wave are brought to rest and further compressed by the following air molecules. This induces a reflected overpressure on the wall which has a greater magnitude than the incident overpressure as shown in Figure 2.23.

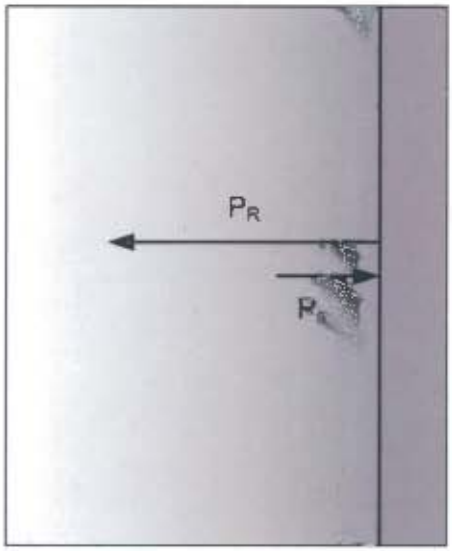


Figure 2.23: Illustration of incident and reflected pressure

The equation for the reflected pressure is given by eq. 2.29, [18].

$$P_r = \frac{2P_s(710+4P_s)}{710+P_s} \text{ (KPa)} \qquad \text{(eq. 2.29)}$$

Where, P_r – reflected pressure, P_s – incident overpressure (KPa)

Following the example from Section 2.2.6 of a 1kg TNT spherical charge detonated at the centre. The charge is placed 1m from a rigid wall. The incident peak overpressure is 1.00MPa. The reflected pressure is calculated using equation (2.29)

$$P_r = \frac{2P_s(710+4P_s)}{710+P_s} = \frac{2\times1000(710+4\times1000)}{710+1000}$$

Therefore,

P_r = 5508.77KPa = 5.51MPa

The value of the reflected pressure is 5.5 times greater than the incident pressure calculated in Section 2.2.6.

2.2.8 Shock waves in tubes

2.2.8.1 Shock tubes

The response of structures subjected to shock loading has been studied for many years using shock tubes. It enables researchers with a simple and efficient way of subjecting structures to shockwaves. A shock tube consists of a high pressure and low pressure section separated by a diaphragm as shown in Figure 2.24. The driver section is pressurised with gas

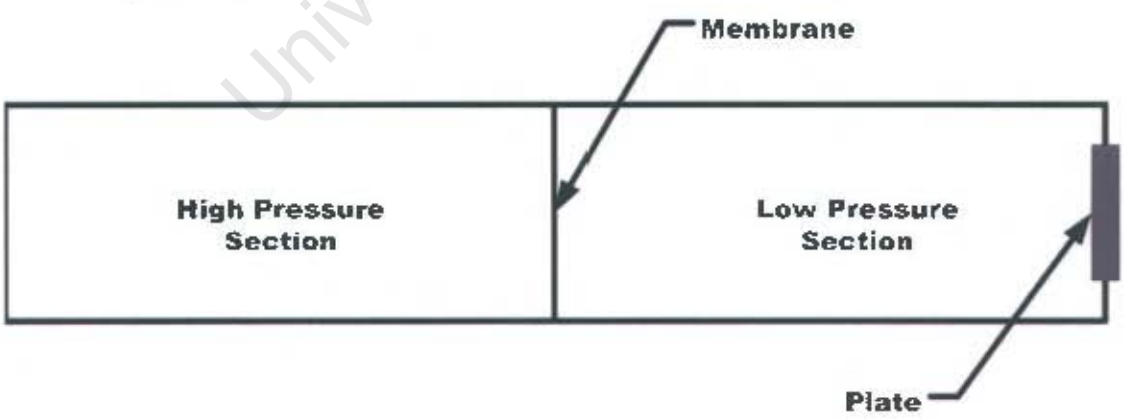


Figure 2.24: Principle of the shock tube, [20]

The high pressure chamber is filled with gas until the membrane is ruptured. A shock wave travels through the low pressure chamber and loads the test plate fixed on the end of the shock tube imparting a high pressure pulse. The pressure-time history of

the load is measured using piezoelectric transducer placed along the length of the shock tube, (Stoffel, [20]).

Shock tubes are designed for different requirements. Kosing and Skews [21] report liquid filled shock tubes used for high speed forming of plates. The pressure energy is used to form metal plates to the desired shape. The liquid shock allows for controlled delivery of the required energy for deformation. A typical pressure-time history for a shock wave travelling down the length of a liquid shock tube is shown in Figure 2.25. The figure shows the pressure-time history of the shock wave at three points along the length of the shock tube. The difference in peak pressure between the top and middle graph is attributed to small loses within the tube. The bottom graph (transducer closest to the plate) shows a sudden drop in pressure due to deformation of the plate. It should be noted that no reflections are observed. This is attributed to complete absorption of pressure energy by the plate deformation process [6].

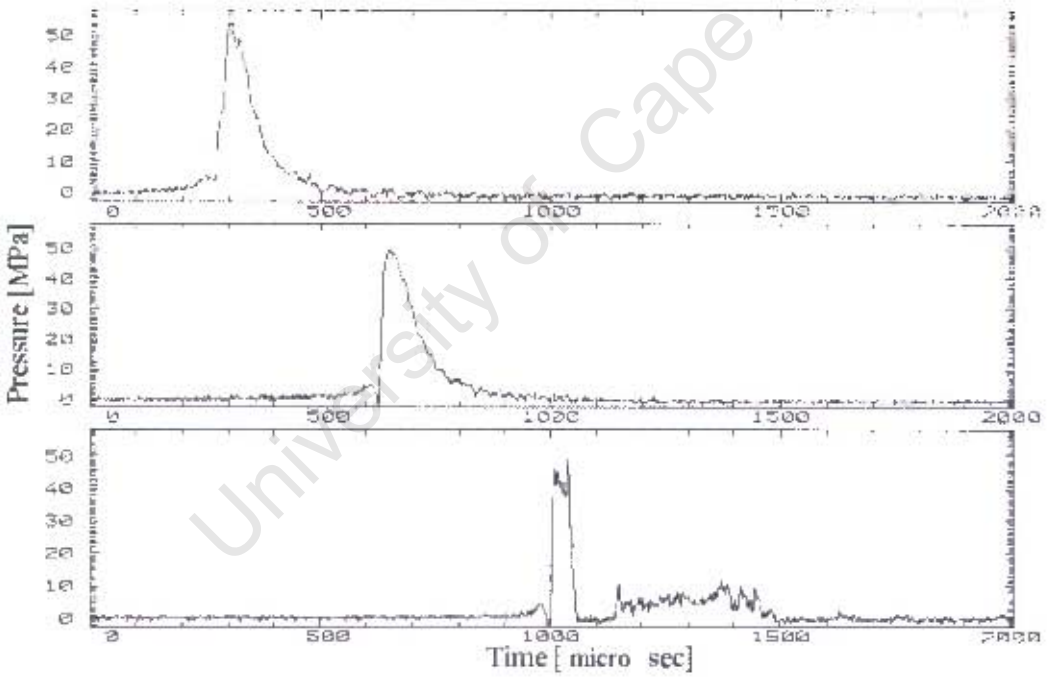


Figure 2.25: Pressure-time history of a shock wave travelling down a shock tube measured at three different locations on the shock tube [21]

2.3 Structural response of plates subjected blast loading

The response of fully clamped metal plates subjected to uniform and localised blast loads has been studied for many years. Experimental work on beams, plates and shells has been widely reported. Nurick and Martin [1, 2] present an overview of theoretical and experimental work conducted in this field pre 1990's. Uniformly distributed impulsive loads were considered. In subsequent years, mild steel plates subjected to circular localised blast loads are reported by Nurick et al [6 – 8].

2.3.1 Impulsive loading – experimental methods

Understanding the response of structures to impulsive loads requires that input and response parameters are well defined and consistent [24]. The following experimental methods are widely used to simulate the response of structures to impulsive loading.

- Air pressure waves generated from explosive devices,
- Impulsive loading using plastic explosives mounted directly, and
- Pressure pulse created using pressure differential between two air chambers.

2.3.1.1 Air pressure generated from explosive devices

An explosive device is detonated in air and structures to be investigated are secured using clamping frames and placed in the path of the pressure wave. Jacinto et al [10] investigated quadrangular steel plates 0.95mm and 2.1mm thick subjected to blast loads using this method. The experimental setup used by Jacinto et al is shown in Figure 2.27. The plate dimensions were 0.95 x 0.95m and 1.0m x 1.5m. The explosive used was Gelamon VF80, with a TNT equivalency of 80%.

Figure 2.27: Photograph of experimental set up used for air pressure generated from explosive devices [10]

The pressure time history of the blast load was recorded using Honeywell 180PC pressure sensors. A typical pressure time history is shown in Figure 2.28. The dynamic response of the plates was measured using accelerometers placed on the plates.

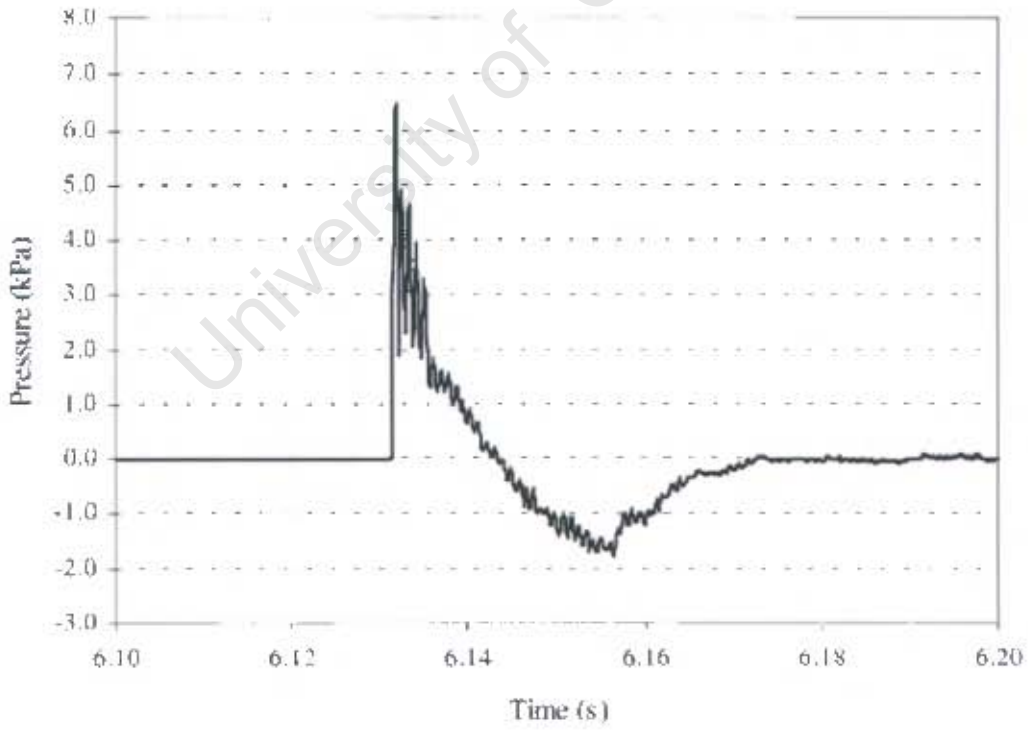


Figure 2.28: Typical pressure time history for air pressure generated from explosive devices [10]

2.3.1.2 *Impulsive loading using plastic explosive mounted directly*

A known mass of plastic explosive is shaped to the required geometry and placed onto polystyrene pads, as shown in Figure 2.29. The polystyrene pad attached to the test specimen is clamped onto a ballistic pendulum as shown in Figure 2.30. The impulse applied by the explosive is measured from the oscillation of the pendulum. This method has been used by Nurick et al. [2 - 8] for uniform and localised blast loading of mild steel plates of different geometries and thicknesses.

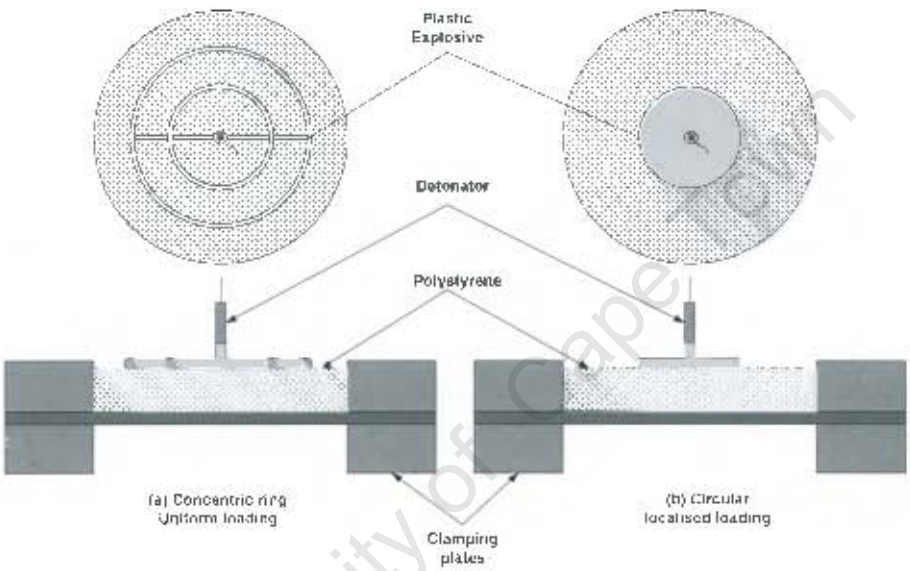


Figure 2.29: Schematic diagram of two different explosive geometries

Figure 2.30: Photograph of experimental set up for impulsive loading using plastic explosive mounted directly

a) *Uniform impulsive loading using plastic explosive mounted directly*

The plastic explosive is laid out in concentric annuli of the shape of the plate, as shown in Figure 2.31 (a) and (b) connected by a cross-leader of explosive. The use of concentric annuli as opposed to using explosive spread over the entire plate area is necessitated by the explosive failing to detonate if charge thickness is less than 2.0mm, as reported by Nurick and Martin [25] using sheet explosive Metabel. This imposes a restriction on the charge mass that can be used, as charge thickness is a function of charge mass and exposed plate area. The arrangement of the concentric annuli is such that there is on average a uniform distribution of explosive mass over the plate [25]. A polystyrene pad is placed between the explosive and plate to prevent spallation of the test plate.

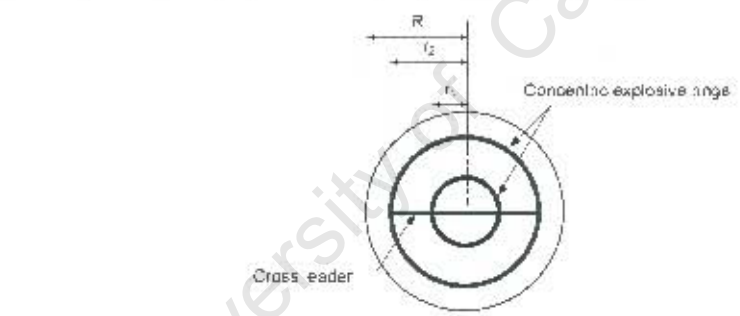
This method was used by Nurick et al [2 - 5].

The concentric annuli are set out as follows:

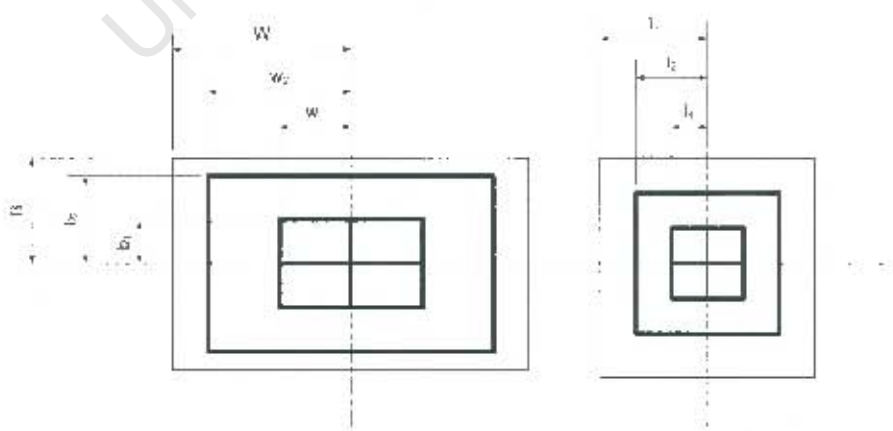
Circular: $r_1 = 0.41R$; $r_2 = 0.82R$

Square: $l_1 = 0.49L$; $l_2 = 0.84L$

Rectangular: $w_1 = 0.50W$; $w_2 = 0.87W$; $b_1 = 0.50B$; $b_2 = 0.87B$



(a) Explosive concentric ring layout for circular plates



(b) Explosive concentric ring layout for quadrangular plates

Figure 2.31: Explosive layout for uniformly loaded circular and quadrangular plates

b) Localised loading using plastic explosive mounted directly

A disc shaped explosive is laid on a polystyrene pad ranging in thickness from 12mm to 16mm. The explosive height and diameter is based on the loading required [6 - 8]. The polystyrene is attached onto the test plate which is clamped between two clamping plates and fixed onto the ballistic pendulum. The general layout of localised loading is shown in Figure 2.32.

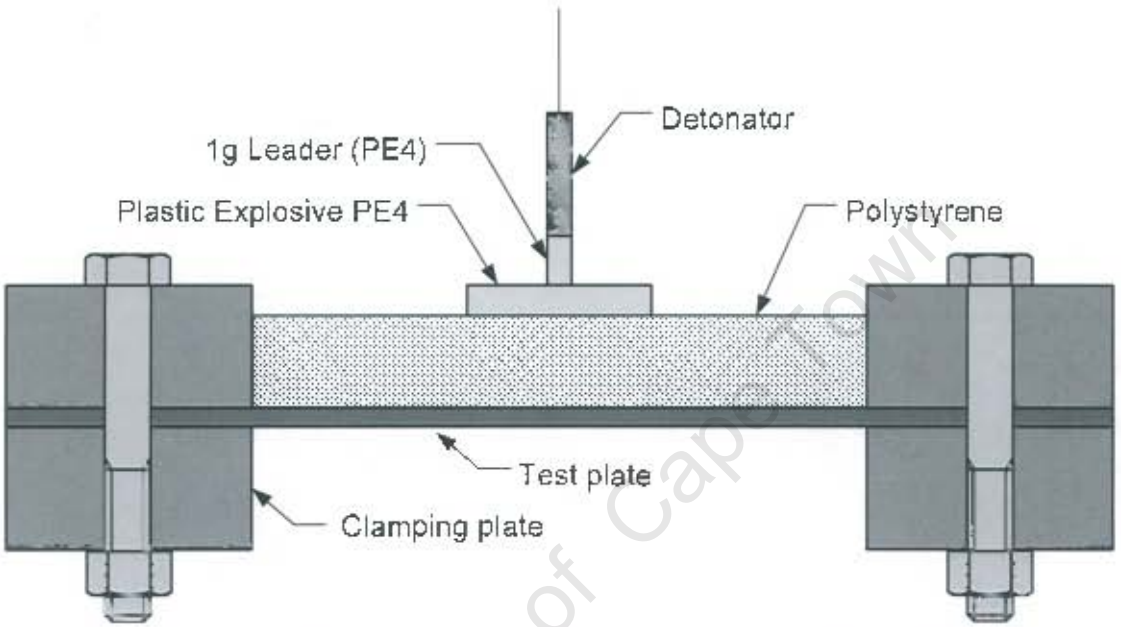


Figure 2.32: Explosive layout for circular localised blast loads

2.3.1.3 *Pressure pulse created using pressure differential between two air chambers*

This method uses pressure differential between two air chambers to impart dynamic load onto the test specimen clamped between the two air chambers via the timed blow-down of the chambers. This method has been shown to produce uniform load distribution across the structure (Langdon [24] and Schleyer et al [26]). The experimental test rig is shown in Figure 2.33. A typical pressure time history of the load is shown in Figure 2.34.

Figure 2.33: Photograph of pressure pulse loading rig [24]

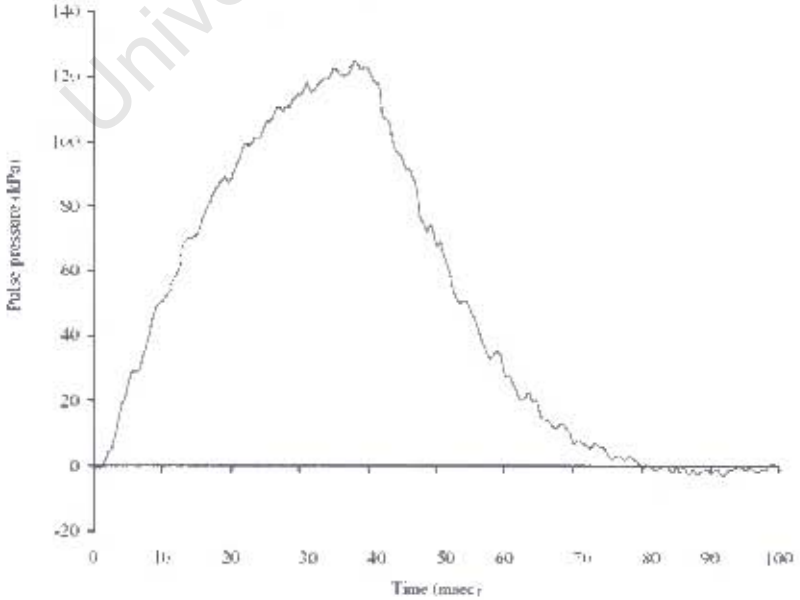


Figure 2.34: Typical pressure time history using pressure pulse loading test rig [26]

2.3.2 Uniformly loaded plates

The studies of impulsive loads on thin disc or circular plates were first conducted during World War II; a review of different experimental work in this field is reported by Nurick and Martin [1].

2.3.2.1 Thin plates subjected to uniform blast load

Experiments on thin mild steel plates subjected to uniform blast loads have been reported by Nurick et al, [2 - 5]. Nurick and Martin, [2] report the development of dimensionless impulse numbers for the different plate geometry (circular and quadrangular) and empirically derived equations for predicting large permanent transverse displacement of the centre of the plate. The failure of circular plates was investigated by Teeling-Smith and Nurick, [5]. The effect of increasing impulse on plate mid-point deflection is reported. It is stated that plate deflection increases with increasing impulse resulting in thinning at the boundary. Further increase in impulse leads to partial tearing along the boundary, followed by complete tearing. The mid-point deflection decreases as impulse is further increased beyond the threshold of complete tearing at the boundary as the failure tends towards complete shear. Figure 2.35 shows the transition in plate deformation reported by Teeling-Smith and Nurick [5]. Analysis was performed to formulate an energy balance equation in terms of input energy and deformation, tearing and disc energy.

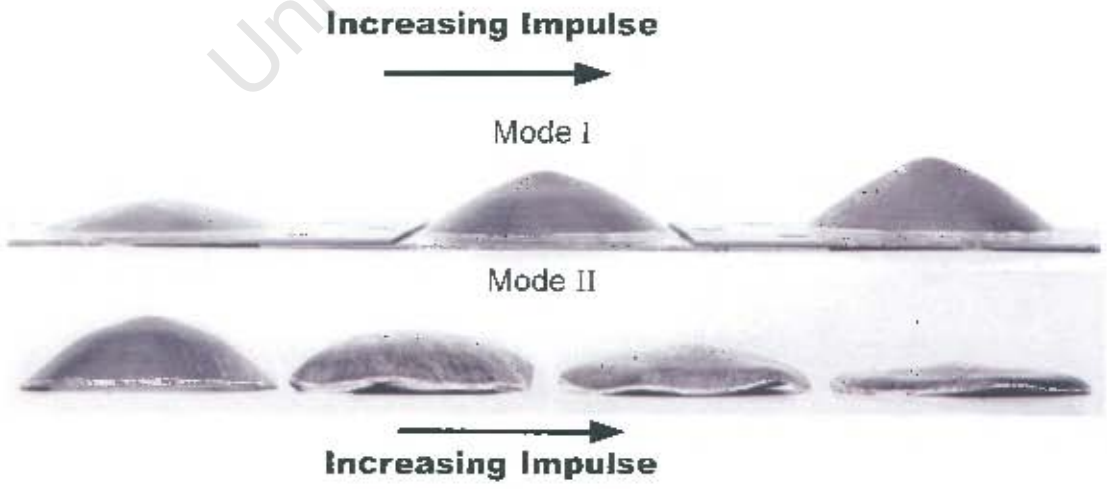


Figure 2.35: Changing mid-point deflection for increasing Impulse (uniformly loaded circular plates) [5]

Experiments on uniformly loaded square plates are reported by Nurick and Shave, [4]. Different failure mechanisms were investigated ranging from large inelastic deformation to partial tearing at the boundary to complete shear. Plate deformations are similar to those reported by Teeling-Smith and Nurick [5] for uniformly loaded circular plates. The mid-point deflection increases for increasing impulse until partial tearing initiates at the middle of one or more sides of the square plate as shown in Figure 2.36. Further increase in impulse results in complete tearing on all sides of the plate with increasing mid-point deflection followed by decreasing mid-point deflection as the plate failure tends towards complete shear at the boundary with no significant mid-point deflection as shown in Figure 2.37.

Figure 2.36: Increasing mid-point deflection for increasing impulse with partial tearing along plate boundary [4]

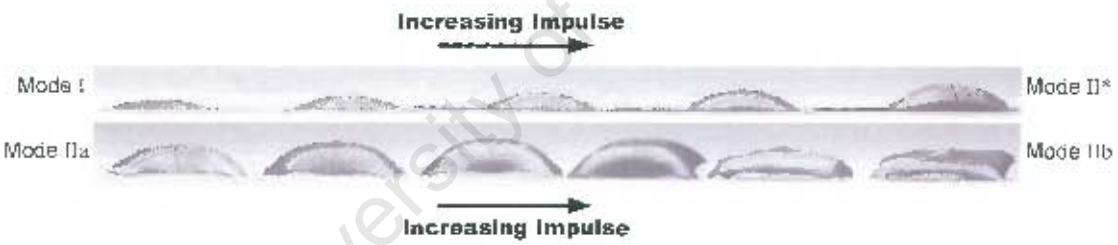


Figure 2.37: Changing mid-point deflection for increasing impulse (uniformly loaded square plates) [4]

2.3.2.2 *Effect of boundary fixation on thin plates subjected to uniform blast load*

The effect of different plate edge fixations is reported by Thomas and Nurick [9]. Fully clamped plates used by Nurick et al [2, 4, 5] were compared to built-in plates machined from 20mm thick mild steel plates to approximate thickness at the test area of 1.6mm, as shown in Figure 2.38. The results showed that, in the case of large inelastic deformation with no tearing at the boundary the mid-point deflection of clamped circular plates and built-in circular plates are generally within ±1 deflection – thickness ratio as shown in Figure 2.39. However it is noted that curvature of the plate deformation near the boundary starts within the clamped region for fully clamped plates. In the case of built-in plates the curvature of plate deformation begins at the boundary as shown in Figure 2.40. Partial tearing along the boundary occurred at lower impulses for built-in plates compared to clamped plates. It is further stated that clamped plates do not fully prevent in-plane movement of the plate during impulsive loading. This behaviour is also reported by Schleyer et al [26] for pulse pressure loaded mild steel plates.

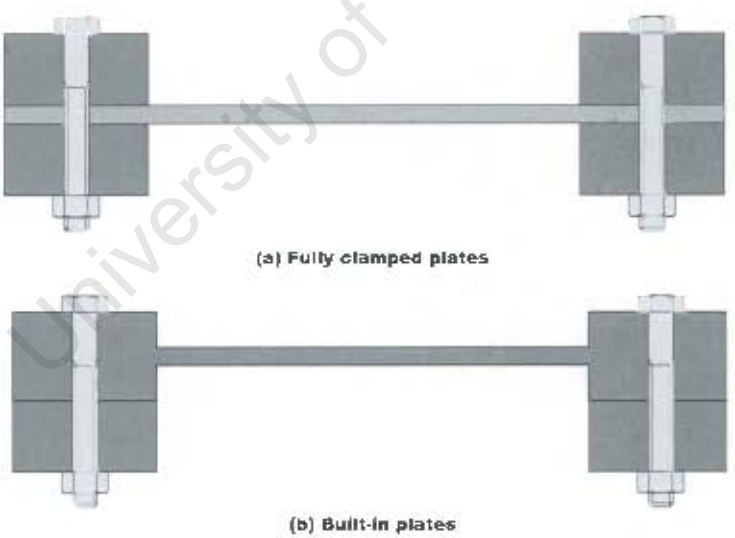


Figure 2.38: Schematic of different plate boundary fixations [9]

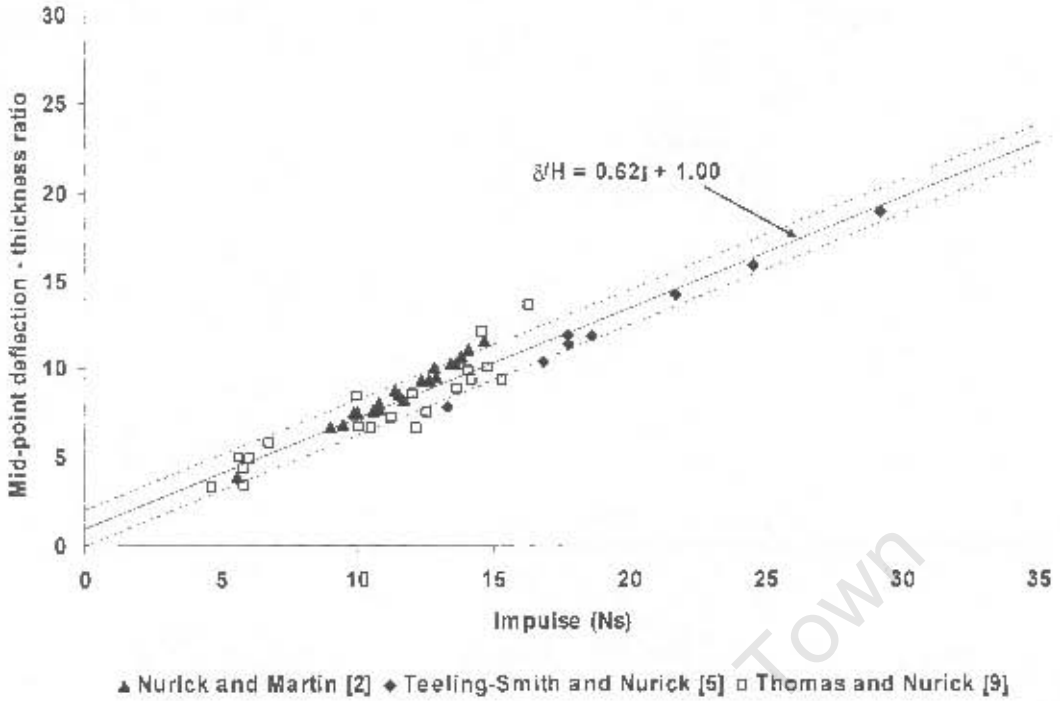


Figure 2.39: Graph of mid-point deflection - thickness ratio versus impulse for large inelastic deformation (Mode I) of fully clamped circular plates [2, 5] and built-in circular plates [9]

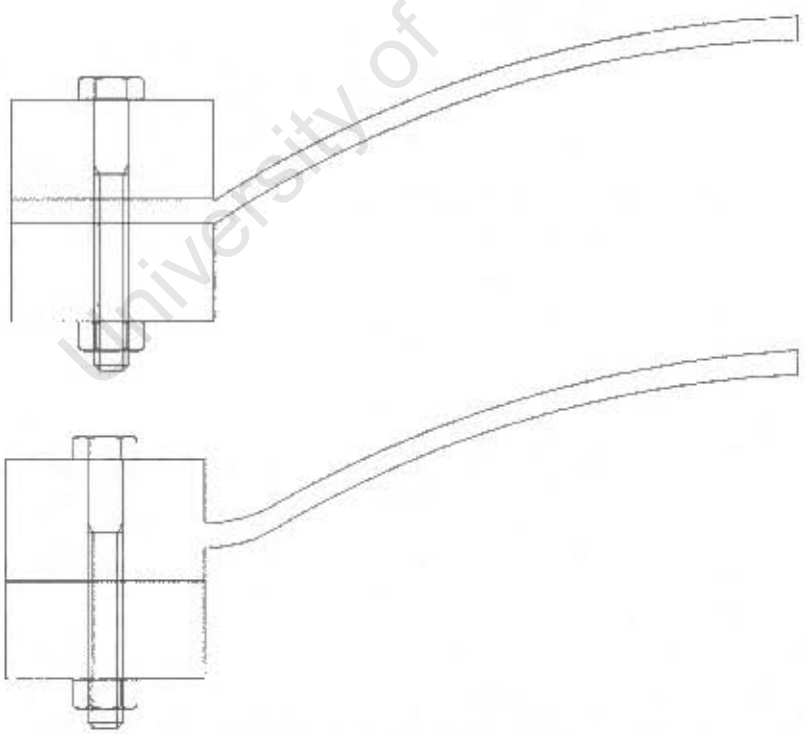


Figure 2.40: Schematic of difference in plate deformation curvature near the boundary for fully clamped and built-in plates [9]

Nurick et al [3] investigated the onset of thinning for different diameter circular mild steel plates clamped between two thicker clamping plates with different edge conditions, as shown in Figure 2.41. The clamps featured sharp edge or fillet radii of 1.5mm or 3.2mm. Observations from the experiments showed that thinning occurred for all plate diameters with sharp edged clamps, however, plates secured using clamping plates with fillets showed larger deflection before the onset of thinning and tearing. The necking at the boundary observed for sharp edged clamps exhibit sharp indentation due to the clamp followed thereafter by stretching and thinning. In the case of curved edge boundary the thinning is similar to that observed in a uniaxial tensile test.

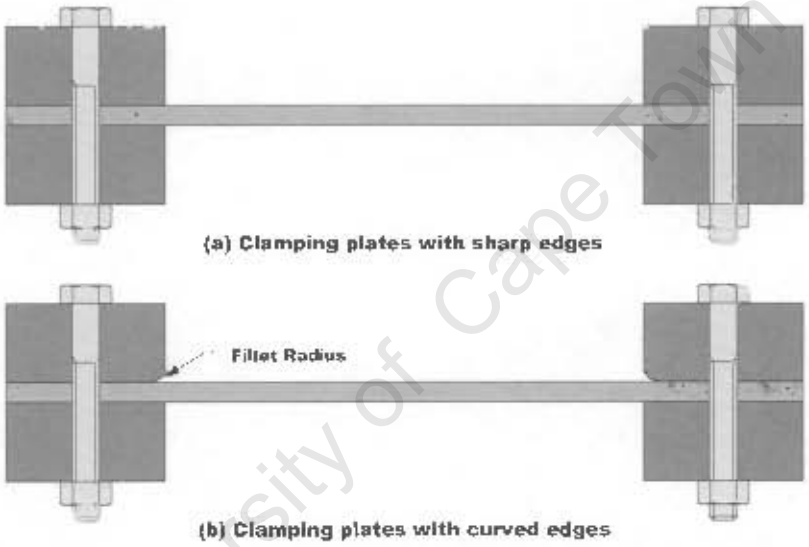


Figure 2.41: Schematic of edge boundary conditions for fully clamped plates [3]

2.3.2.3 Effect of stiffeners on thin plates subjected to uniform blast load

Nurick et al [27, 28] report experiments using stiffened plates. The stiffeners and the plate were two separate components clamped together by two support plates. The test plates with the stiffeners were subjected to uniform blast loads. Nurick et al [29] also report on experimental work on built-in stiffened quadrangular plates. The stiffener, plate and boundary are machined from 12mm thick plate as shown in Figure 2.42. Chung Kim Yuen and Nurick [30] report an experimental investigation into the influence of different stiffener configurations as shown in Figure 2.43. The results indicated that for large inelastic deformation there was a general trend of increasing permanent displacement with increasing impulse similar to un-stiffened plates. In case of tearing at the boundary, the behaviour is similar to that of un-

stiffened square plates. The tearing occurs at the middle of the sides and then progresses towards the corners as the impulse increases. Chung Kim Yuen and Nurick [30] report that tearing is not reduced by stiffening the plates. The stiffeners restrict the plate to deform plastically causing tearing to occur at an impulse that would normally cause an un-stiffened plate to deform. Other experimental work has been reported by Langdon et al [31] on stiffened plates subjected to localised blast loads. The results show increased influence of stiffener configuration. A stiffener located along the mid-line of the plate significantly reduced the overall plate deformation. However, premature tearing occurred at the plate – stiffener interface rather than at the boundary as reported by Chung Kim Yuen and Nurick [30] for uniformly loaded stiffened plates.

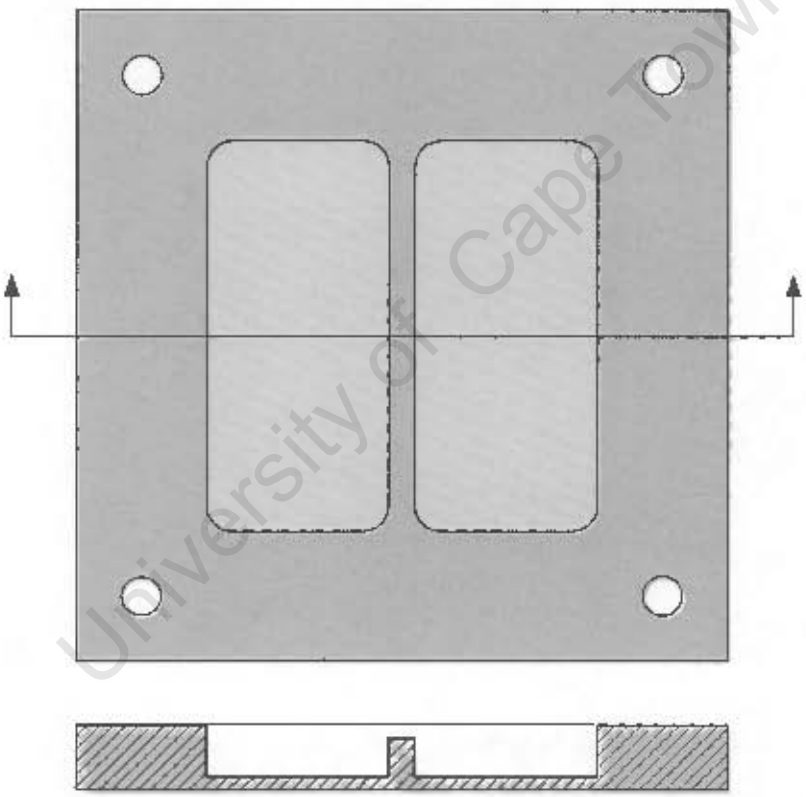


Figure 2.42: Schematic drawing of a built-in plate showing required stiffener configuration machined from 12mm thick mild steel base plate [29]

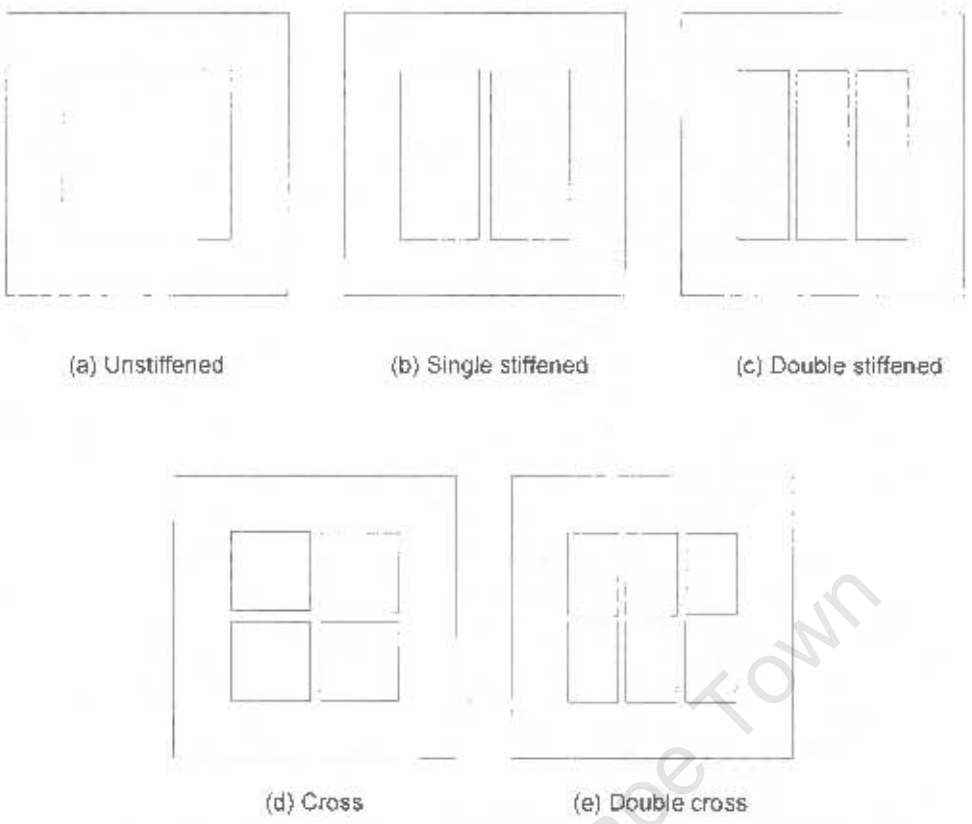


Figure 2.43: Schematic drawing of different stiffener configuration [31]

2.3.2.4 Modes of failure for thin plates subjected to uniform blast loads

Failure modes of structures were first classified by Menkes and Opat [32], for blast loaded beams.

Mode I – Large inelastic deformation of the entire beam

Mode II – Tearing (tensile failure) of the beam material at the supports

Mode III – Transverse shear failure of the beam material at the supports

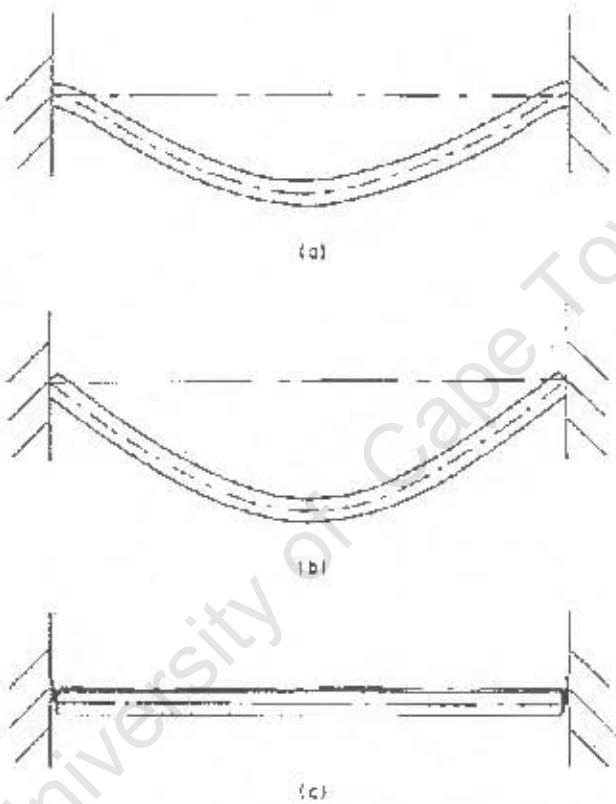


Figure 2.44: Permanent plate deformations (a) Mode I, (b) Mode II and (c) Mode III

Nurick et al [15] further subdivided Mode I failure to describe necking partially and completely around the plate boundary.

Mode Ia – Large inelastic deformation with necking around part of the boundary

Mode Ib – Large inelastic deformation with necking around the entire boundary

The lower bound of Mode Ia is the phase where some part of the boundary exhibits necking. As the load is increased, necking progresses to cover the entire boundary, (upper bound of Mode I) and is designated as Mode Ib failure.

Further increase in load exhibit the transition from Mode I type failure to Mode II. The lower bound of Mode II failure is manifested in the plate as tearing along part of the boundary and is classified as Mode II*. Further classification of the Mode II failure included the case of increasing mid-point deflection for increasing impulse. Further increases in impulse resulted in reduced mid-point deflection similar to those for Mode III failure [4].

Mode II* – Large inelastic deformation with partial tearing around part of the boundary

Figure 2.45: Increasing mid-point deflection for increasing impulse with partial tearing along plate boundary [4] (repeated figure)

Mode IIa – Increasing mid-point deflection with increasing impulse with complete tearing at the boundary

Mode IIb – Decreasing mid-point deflection with increasing impulse with complete tearing at the boundary

Figure 2.46: Changing mid-point deflection for increasing impulse (uniformly loaded square plates) [4] (repeated figure)

2.3.3 Localised blast loaded plates

Experiments on circular clamped mild steel plates subjected to localised blast loads are reported by Nurick and Radford. [6]. The test methodology is the same as discussed in Section 2.3.1.2. The plate deformation is characterised by an inner dome superimposed on a larger global dome, as shown in Figure 2.47. This plate deformation shape was later observed by Chung Kim Yuen and Nurick for built-in circular plates, [7] and Jacob et al for quadrangular plates subjected to localised loads, [8].

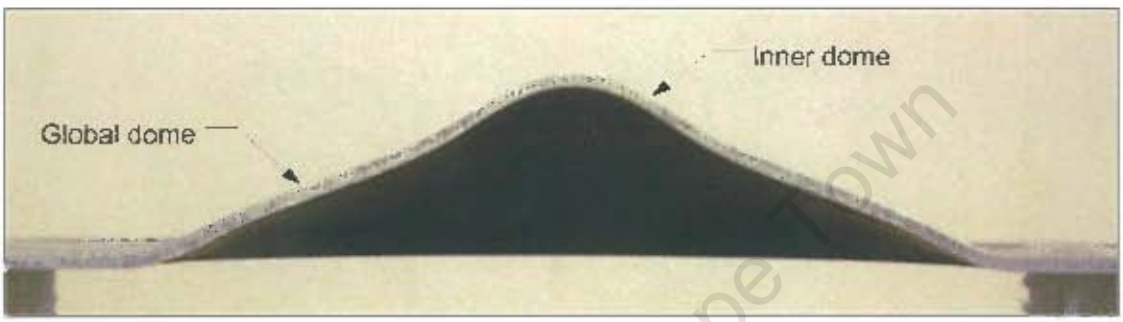


Figure 2.47: Large inelastic deformation for localised blast loaded plate

Modes of failure reported include large inelastic deformations, thinning at the central area and boundary of the plate. Tearing at the central area of the plate occurs with further increase in impulse after the onset of thinning. The tearing observed is characterised by a cap shaped piece tearing away from the plate. Tearing at the boundary is observed for larger load diameter – plate diameter ratios.

It should be noted that the thinning mechanism at the central area and at the boundary are different. In the case of thinning at the boundary, it is defined by the nature of the clamping frames. Sharp edge clamping frames result in plate thinning at the boundary similar to indentation as reported by Nurick et al [3].

2.3.3.1 Modes of failure for thin plates subjected to localised blast loads

The range of plate failure modes observed for localised blast loading are large inelastic deformation (Mode I) to complete tearing at the boundary (Mode II), [6 - 8]. Complete shearing (Mode III) has not been observed. The modes of failure refined by Nurick and Radford [6] to suit plate response for localised blast load are given in Table 2.1

Several modes of failure are obviously common to both uniform and localised blast loading, these are highlighted in Table 2.2 listing a summary of the modes of failure.

Table 2.1: Modes of failure for plates subjected to localised blast loading

	*Mode I – Large Inelastic deformation*		*Mode IIc – Complete tearing in the central area – capping*
	*Mode IIc – Large inelastic deformation with thinning in the central area*		*Mode II – Complete tearing at the boundary*
	*Mode Ib – Large inelastic deformation with thinning at the boundary*		*Petalling*
	*Mode II*c – Partial tearing in the central area*		

Table 2.2: Summary of modes of failure for plates subjected to uniform and localised blast loads

Modes of Failure	Description	Uniform loading	Localised loading
Mode I	large inelastic deformation	✓	✓
Mode Ia	large inelastic deformation with necking around part of the boundary	✓	
Mode Ib	large inelastic deformation with necking around the entire boundary	✓	✓
Mode Itc	large inelastic deformation with thinning in the central area		✓
Mode II	tensile tearing at the boundary	✓	✓
*Mode II**	large inelastic deformation with partial tearing around part of the boundary	✓	✓
Mode IIa	increasing mid-point deflection with increasing impulse with complete tearing at the boundary	✓	
Mode IIb	decreasing mid-point deflection with increasing impulse with complete tearing at the boundary	✓	
*Mode II*c*	partial tearing in the central area		✓
Mode IIc	Complete tearing in the central area – capping		✓
Mode III	transverse shear failure at the boundary	✓	
Petalling			✓

2.4 Influence of stand-off distance and charge mass on large inelastic deformation of plates

The relationship between stand-off distance and plate deformation due air blast experiments is not widely reported.

Experimental studies using air blast loading to understand the effect of stand-off distance on plate deformation have been reported by Akus and Yildirim [11]. They report experiments using 240 x 240mm steel square plates of 1mm thickness. Experimental parameters are given Table 2.3.

Table 2.3: Experimental set up data, [11]

Charge mass (g)	Charge mass (TNT equivalent) (g)	Stand-off distance (mm)
131	200	200, 225, 250, 300, 400, 500, 600
163.7	250	200, 225, 250, 300, 400, 500
196.4	300	250, 400, 500, 600
261.9	400	250, 400, 500, 600
392.9	600	250, 400, 500, 600
654.8	1000	250, 400, 500, 600

2.4.1 Plate mid-point deflection and stand-off distance [11]

The graph of mid-point deflection versus stand-off distance [11] as shown in Figure 2.48, indicates maximum mid-point deflection at the closest stand-off distance of 200mm followed by a rapid decrease up to stand-off distance of 300mm. The mid-point deflections decrease gradually between stand-off distances of 400mm to 600mm for charge masses ranging from 131g to 261.9g. However, for charge masses 392.9g and 654.8g the mid-point deflection decreases sharply between stand-off distances of 400mm and 600mm. Hence indicating that, the gradual decrease in mid-point deflection with respect to stand-off distance is a function of charge mass.

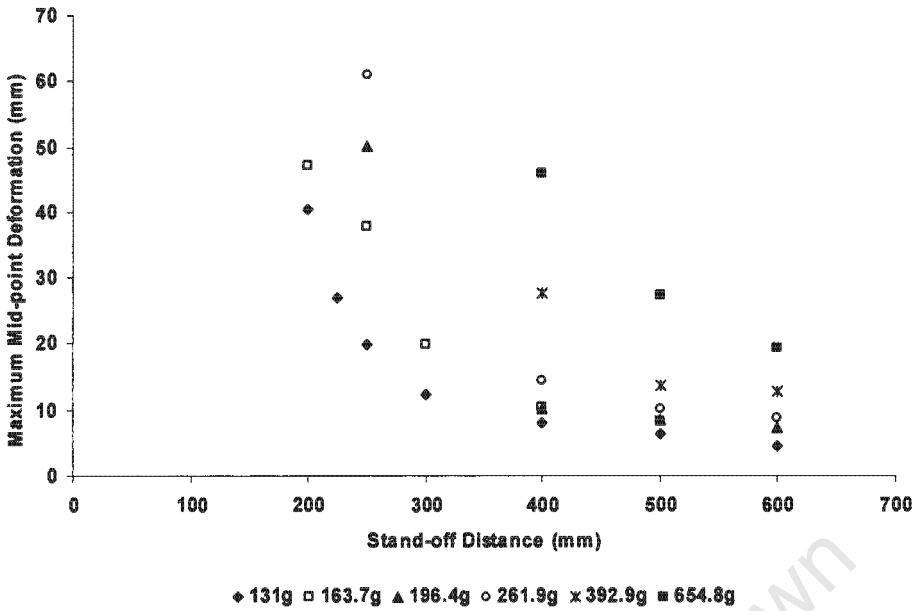


Figure 2.48: Maximum mid-point deformation changing with stand-off distance [11]

2.4.2 Plate mid-point deflection and charge mass

The graph of mid-point deflection versus charge mass [11] as shown in Figure 2.49, indicate that mid-point deflection increases with increasing charge mass for a given stand-off distance. The increase in mid-point deflection is dependent on stand-off distance. At the closest distance the deflection increases rapidly as charge mass is increased. Whilst, moving the explosive further away from the test plate results in a more gradual increase in mid-point deflection for increasing charge mass.

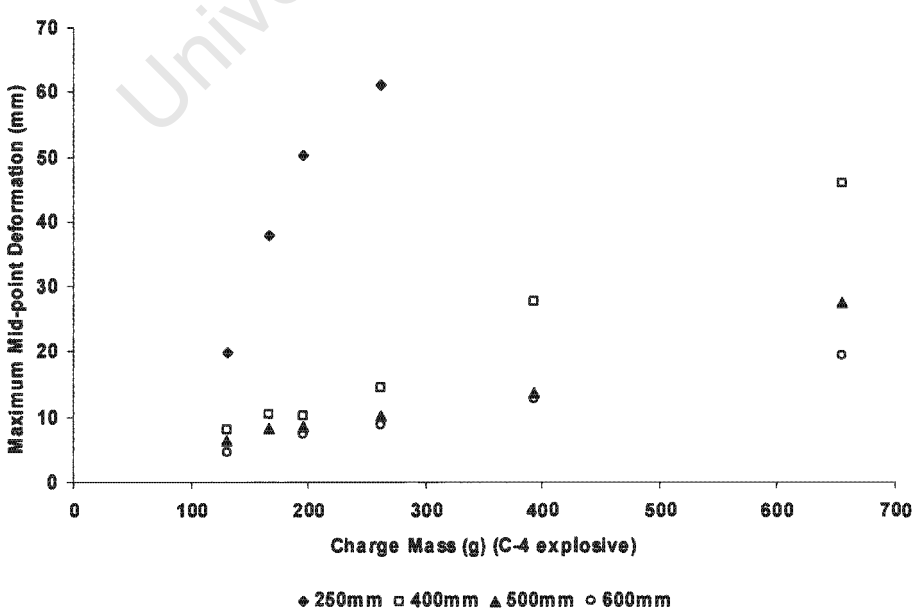


Figure 2.49: Maximum mid-point deformations changing with charge mass [11]

2.4.3 Relationship between stand-off distance on blast loading condition

Marchand and Alfawakhiri [33] suggest a guide for assumption of uniform blast load over a structure. If the charge stand-off exceeds one-half of the structure's width or height (largest dimension), then loads can be reasonably averaged over the structure provided the charge is centred on the structure

In the case of circular disc shaped explosive charge placed at a certain stand-off distance, S, from a circular metal plate of diameter D. The blast load is said to be applied uniformly over the entire plate area for stand-off greater than plate radius (S ≥ D/2). Conversely, focusing of the blast load occurs at stand-off distance less than plate radius (S ≤ D/2). Hence the plate is subjected to localised blast loads.

An illustration of the ranges of stand-off distance in relation to uniform and localised loading regimes is shown in Figure 2.50.

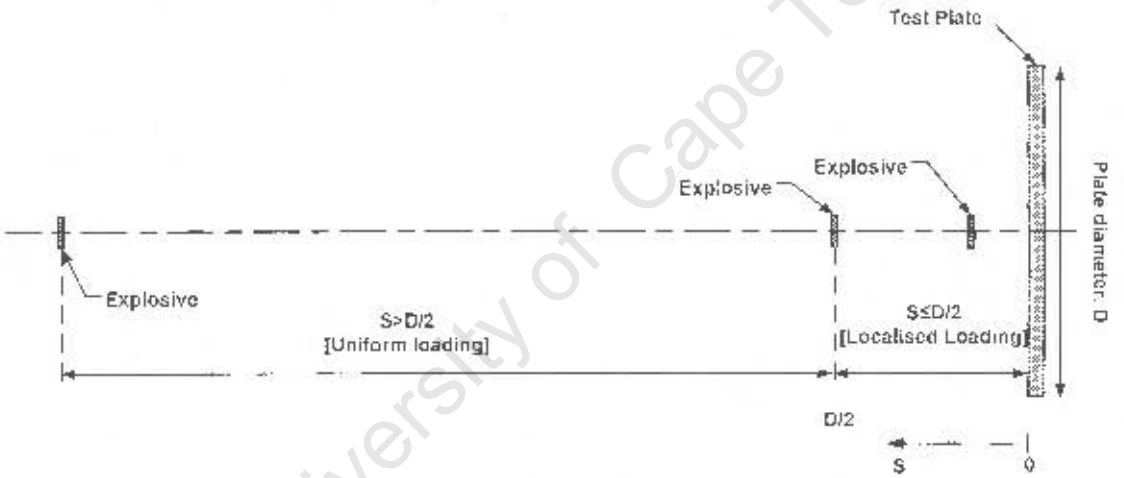


Figure 2.50: Illustration of charge stand-off distance and loading condition

2.5 Theoretical predictions

Theoretical predictions of plates subjected to impulsive loading have been reported for many years, (Nurick and Martin [2]).

2.5.1 Jones damage number for fully clamped rigid circular and Quadrangular plates

2.5.1.1 Jones damage number for circular plates

Jones, [34] proposed a damage number λ to predict large inelastic deformation of fully clamped circular plates loaded impulsively by an uniformly distributed velocity, V_o as shown in Figure 2.51.

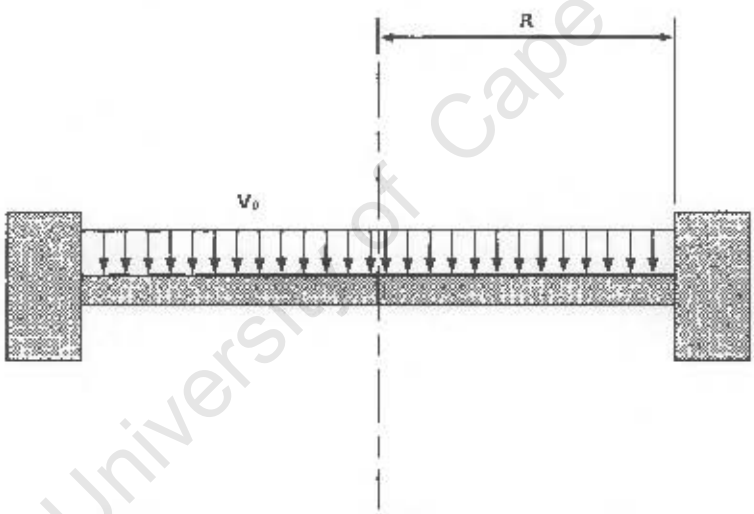


Figure 2.51: Fully clamped circular plate with radius R subjected to a uniformly distributed impulsive velocity Vo, [34]

The damage number λ is a dimensionless initial kinetic energy term.

$$\lambda = \frac{\mu V_o^2 R^2}{M_o H} \qquad \text{(eq. 2.30)}$$

Where, μ - Mass per unit area (ρH), M_o - $\sigma_o H^2/4$, V_0 - Initial velocity, R - Plate radius, H - Plate thickness

Jones damage number (equation 2.30) can be written in terms of impulse as follows,

$$\lambda = \frac{\mu V_o R^2}{M_o H} = \frac{(\rho H) V_o^2 R^2}{\left(\frac{\sigma_o H^2}{4}\right) H} = \frac{4 \rho V_o^2 R^2}{\sigma_o H^2} \quad \text{(eq. 2.31)}$$

Impulse is given by

$$I = m V_o \quad \text{(eq. 2.32)}$$

Where I – Impulse, m – mass of plate ($\pi R^2 H \rho$)

$$V_o = \frac{I}{m} \quad \text{(eq. 2.33)}$$

$$V_o = \frac{I}{\pi R^2 H \rho} \quad \text{(eq. 2.34)}$$

Substituting equation (2.34) into equation (2.31) and simplifying gives

$$\lambda = \frac{4 I^2}{\pi^2 R^2 H^4 \rho \sigma_o} \quad \text{(eq. 2.35)}$$

Where, ρ – plate density, σ_o – static yield stress

The large permanent transverse displacement of the centre of the plate is given by

$$\delta / H = \frac{\left[1 + 2\lambda / 3\right]^{1/2} - 1}{2} \quad \text{(eq. 2.36)}$$

Where, δ – permanent transverse displacement

2.5.1.2 *Jones damage number for quadrangular plates*

Jones damage number for quadrangular plate is given as

$$\lambda = \mu V_0^2 L^2 / M_0 H \quad \text{(eq. 2.37)}$$

Written in terms of impulse as follows,

$$\lambda = 4 I^2 L^2 / A_0^{\,2} \rho \sigma_0 H^4 \quad \text{(eq. 2.38)}$$

Where L – plate half length, A_o – loaded area (in this case, A_o = 2B x 2L)

The large permanent transverse displacement of the centre of the plate is given by

$$\delta/H = \frac{(3-\xi_0)\left\{\left[1+\frac{1}{6}\lambda\xi_0^{\,2}\left(1-\xi_0+\frac{1}{2-\xi_0}\right)\right]^{1/2}-1\right\}}{\{2[1+(\xi_0-1)(\xi_0-2)]\}} \qquad \text{(eq. 2.39)}$$

Where, B – plate half width, $\xi_0 = B/L \tan\phi$ and $\tan\phi = -B/L + \left[3+(B/L)^2\right]^{1/2}$

For example, the mid-point deflection of square and rectangular plates is determined as follows,

a) Square plate of half – width to half – length ratio (B/L) equal to one, as shown in Figure 2.51(a).

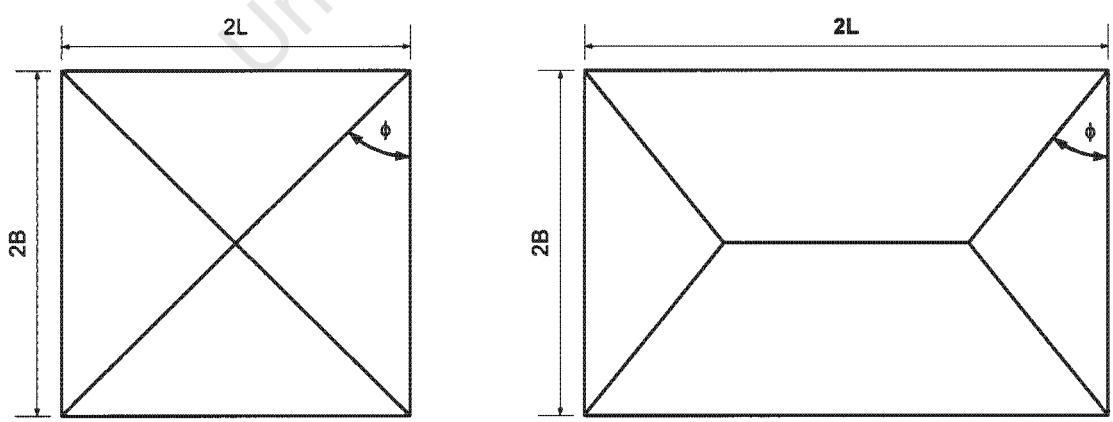
$$\tan\phi = -B/L + \left[3+(B/L)^2\right]^{1/2} = -1+\left[3+1^2\right]^{1/2} = 1$$

and

$$\xi_0 = B/L \tan\phi = 1$$

Therefore, equation (2.39) simplifies to:

$$\delta/H = \frac{(3-1)\left\{\left[1+\frac{1}{6}\lambda 1^2\left(1-1+\frac{1}{2-1}\right)\right]^{1/2}-1\right\}}{2[1+(1-1)(1-2)]} = \underline{\sqrt{1+\lambda/6}-1}$$



(a) Square plate (B/L = 1) (b) Rectangular plate (B/L = 0.5)

Figure 2.52: Schematic of uniformly loaded square and rectangular plates showing plan view of plastic hinge lines

b) Rectangular plate of half – width to half – length ratio (B/L) equal to 0.5, as shown in Figure 2.51(b).

Hence L = 2B

$$\tan\phi = -B/L + \left[3 + (B/L)^2\right]^{1/2} = -B/2B + \left[3 + (B/2B)^2\right]^{1/2} = -1/2 + \left[3 + (1/2)^2\right]^{1/2} = 1.3$$

and

$$\xi_0 = B/L \tan\phi = 1.3(B/2B) = 0.65$$

Therefore, equation (2.39) simplifies to:

$$\delta/H = \frac{(3-0.65)\left\{\left[1+\frac{1}{6}\lambda(0.65)^2\left(1-0.65+\frac{1}{2-0.65}\right)\right]^{1/2}-1\right\}}{2[1+(0.65-1)(0.65-2)]}$$

Thus,

$$\delta/H = \underline{0.80\left[\sqrt{1+0.13\lambda}-1\right]}$$

2.5.2 Nurick and Martin damage number for uniform and localised loaded circular and quadrangular plates

Nurick and Martin [2] proposed modified dimensionless damage numbers for quadrangular and circular plates loaded impulsively based on Johnson's damage number, given as

$$\alpha = \frac{\rho v^2}{\sigma_d} \qquad \text{(eq. 2.40)}$$

Where, ρ – material density, v – impact velocity, σ_d – damage stress

However, Johnson's damage number does not consider method of impact, target geometry or boundary conditions.

Johnson's damage number can be written in terms of impulse as follows

$$I = mv \qquad \text{(eq. 2.41)}$$

Where, I – Impulse, m – mass of plate ($A_o H\rho$)

$$v = \frac{I}{m} \qquad \text{(eq. 2.42)}$$

$$v = \frac{I}{A_o H\rho} \qquad \text{(eq. 2.43)}$$

Where, A_o – load area, H – plate thickness

Thus substituting equation (2.43) into equation (2.40) gives

$$\alpha = \frac{I^2}{A_o^2 H^2 \rho\sigma_d} = \frac{I_o^2}{H^2 \rho\sigma_d} \qquad \text{(eq. 2.44)}$$

Where, I_o – impulse per area (I/A_o)

Nurick and Martin introduced a geometrical damage number

$$\psi = \left[\beta\alpha\left(\frac{A_o}{A}\right)^2\right]^{1/2} \qquad \text{(eq. 2.45)}$$

Where, β – geometry number (plate length, l to plate width, b ratio), A – plate area

A relationship between the distance from plate centre to the nearest boundary and plate thickness was introduced (termed Aspect ratio, λ)

For circular plate

$$\lambda = \frac{R}{H} \qquad \text{(eq. 2.46)}$$

For quadrangular plate

$$\lambda = \frac{b}{2H} \qquad \text{(eq. 2.47)}$$

A loading parameter in terms of loading area per total plate area was introduced for circular plates only.

$$\zeta = 1 + \ln\left(\frac{R}{R_o}\right) \qquad \text{(eq. 2.48)}$$

Where, R – Plate radius, R_o – radius of the loaded area

This implies that as R_o tends to R, ζ tends to a value of one. Thus the plate is uniformly loaded over the entire test area. A schematic illustration is shown in Figure 2.53.

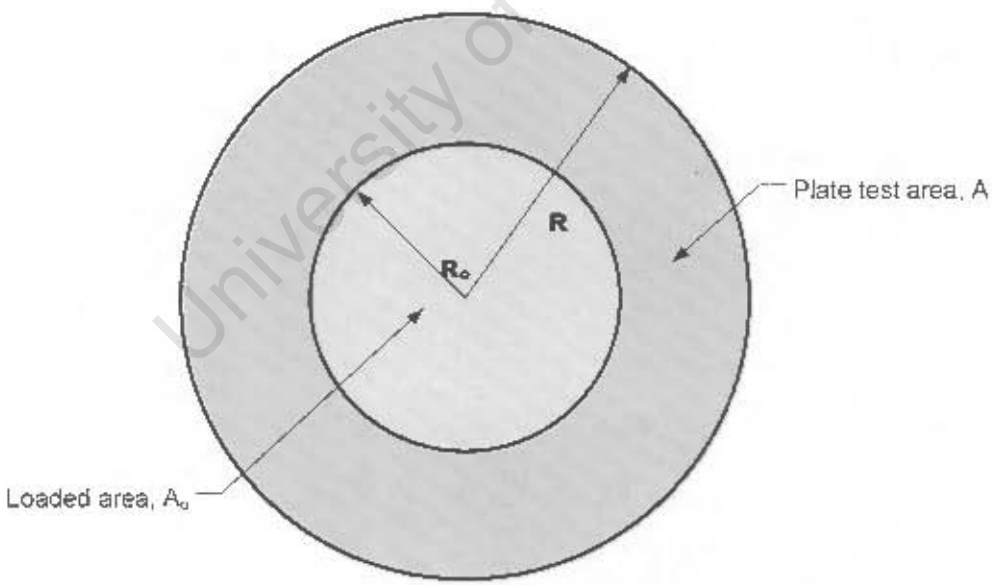


Figure 2.53: Schematic of loading condition for circular plates

Combining equations 2.45 to 2.48 results in a modified damage number which incorporates dimensions and loading:

$$\phi = \psi\lambda\zeta \qquad \text{(eq. 2.49)}$$

For circular plate (uniform impulsive load, ζ=1)

$$\phi_c = \frac{I}{\pi R H^2 (\rho\sigma_0)^{1/2}} \qquad \text{(eq. 2.50a)}$$

For circular plate (localised impulsive load)

$$\phi_c = \frac{I\left(1+\ln\frac{R}{R_0}\right)}{\pi R H^2 (\rho\sigma_0)^{1/2}} \qquad \text{(eq. 2.50b)}$$

For quadrangular plate (uniform impulsive load)

$$\phi_q = \frac{I}{2H^2 (bl\rho\sigma_0)^{1/2}} \qquad \text{(eq. 2.51)}$$

It should be noted that damage stress is replaced by static yield stress, σ_o.

For quadrangular plate (localised impulsive load)

A modification to damage number ϕ_q is reported by Jacob et al [8] for quadrangular plates subjected to localised blast loading. A loading parameter ζ_{ql} similar in form to equation (2.48) is incorporated into ϕ_q (eq. 2.51). The loading parameter is a function of plate area and load (charge) area written as,

$$\zeta_{ql} = 1+\ln\left(\frac{lb}{\pi R_0^{\,2}}\right) \qquad \text{(eq. 2.52)}$$

The modified damage is written as

$$\phi_{ql} = \phi_q \zeta_{ql} \qquad \text{(eq. 2.53)}$$

$$\phi_{ql} = \frac{I\left(1+\ln\left(\frac{lb}{\pi R_0^{\,2}}\right)\right)}{2H^2 (bl\rho\sigma)^{1/2}} \qquad \text{(eq. 2.54)}$$

The difference between loading parameter ζ (equation (2.48)) and ζ_{ql} (equation (2.52)) is the geometrical similarity between the charge shape and plate in the case of circular plates subjected to blast loads using circular disc shaped explosives, hence the ratio of radii of the plate and charge is used. Whilst in the case of quadrangular plate subjected to blast loads using circular disc shaped explosives,

there is no geometrical similarity, as a result the ratio of areas of plate and charge is used.

An empirical relationship between permanent plate mid point deflection-thickness ratio and damage number is reported [2] for circular and quadrangular plates as follows

For circular plates

$$\frac{\delta}{H} = 0.425\phi_c \qquad \text{(eq. 2.55)}$$

For quadrangular plates

$$\frac{\delta}{H} = 0.48\phi_q \qquad \text{(eq. 2.56)}$$

2.5.3 Deformation strain energy analysis

Impulsive loading of plates are accompanied by large plastic deformation at high strain rates. Therefore it is necessary to compute the strain energy of plastic deformation of test specimens. The following is a summary of discussion given by Ezra [35].

The stress-strain relations are an important element in the calculation of the strain energy. At high strain rates the strain energy can be substantially different from values obtained from static or slow strain rate tests. In the case of plates subjected to explosive blast loading, high strain rates occur during the initial stages of deformation and decrease rapidly to zero by the end of the deformation process. Therefore any deviation of the stress-strain relationship from static values would occur during the initial stages of deformation and hence would not necessarily affect the computation of plastic strain energy appreciably.

The strain energy per unit volume dU_{strain}, which is caused by a small increase in strain, is given by

$$dU_{strain} = \sigma_1 d\varepsilon_1 + \sigma_2 d\varepsilon_2 + \sigma_3 d\varepsilon_3 \qquad \text{(eq. 2.57)}$$

Where, σ_1, σ_2, σ_3 are principal true stresses: ε_1, ε_2, ε_3 are principal true strains. The true stress is defined as the load divided by instantaneous cross-sectional area. The true strain is defined as follows: considering a tensile specimen with initial length l_o, instantaneous length l and instantaneous length increment dl, thus

$$d\varepsilon = \frac{dl}{l} \qquad \text{(eq. 2.58)}$$

Integrating equation (2.58) yields

$$\varepsilon = \int_{l_o}^{l} \frac{dl}{l} = \ln \frac{l}{l_o} \qquad \text{(eq. 2.59)}$$

It is noted that engineering strain defined by the change in length divided by the original length l_o cannot be used when deformations are large.

Using St. Venant's theory of plastic flow based on the assumption that plate material volume does not change during deformation, it follows that equation (2.57) is equivalent to

$$dU_{strain} = \sigma_{eff} d\varepsilon_{eff} \qquad \text{(eq. 2.60)}$$

Where,

$$\sigma_{eff} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \qquad \text{(eq. 2.61)}$$

$$\varepsilon_{eff} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} \qquad \text{(eq. 2.62)}$$

For most strain hardening materials the following stress-strain relationship can be used

$$\sigma_{eff} = K\varepsilon_{eff}^{n} \qquad \text{(eq. 2.63)}$$

The values for K (strength coefficient) and *n* (strain hardening exponent) are obtained from uni-axial tensile tests where $\sigma_1=\sigma_{eff}$ and $\varepsilon_1=\varepsilon_{eff}$.

The strain energy per unit volume, U_{strain} for a strain hardening material is obtained by substituting equation (2.63) into (2.60) and integrating,

$$U_{strain} = \frac{K}{n+1}\varepsilon_{eff}^{n+1} \qquad \text{(eq. 2.64)}$$

For non-strain hardening materials with constant yield stress, $\sigma_{eff}=\sigma_o$, the yield stress in a uni-axial tensile test, substituting this into equation (2.60) gives

$$U_{strain} = \sigma_o \varepsilon_{eff} \qquad \text{(eq. 2.65)}$$

Total strain energy per unit volume is obtained by integrating either equation (2.65) or (2.64) over the total volume of the deformed plate.

$$U_T = \int U_{strain} dV \qquad \text{(eq. 2.66)}$$

Where, dV is the elemental volume of the material.

For the case of a circular plate with large deformation consider the case shown in Figure 2.54. A plate deformation in the shape of a circular dome formed due to an explosive charge. Let the initial plate thickness be H_o, δ, the plate mid-point deflection and r, the radius of curvature of the segment of the sphere.

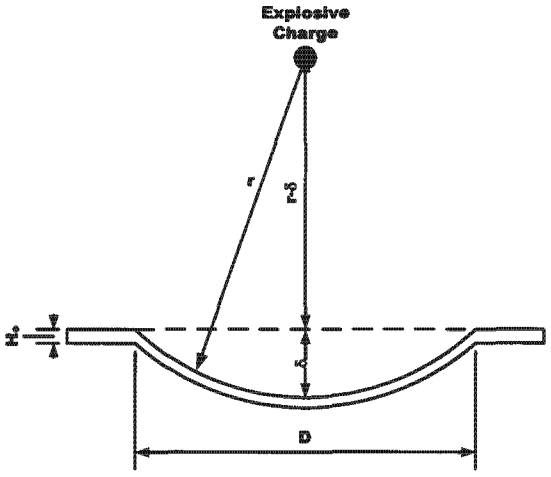


Figure 2.54: Explosively formed dome

From geometric considerations

$$r^2 = \frac{D^2}{4} + (r-\delta)^2 \qquad \text{(eq. 2.67)}$$

Rearranging equation (2.67) yields

$$2r\delta = \frac{D^2}{4} + \delta^2 \qquad \text{(eq. 2.68)}$$

The surface area of the circular dome is given by the integral

$$Area = 2\pi r \int_{r-\delta}^{r} dx = 2\pi r\delta \qquad \text{(eq. 2.69)}$$

Hence the volume of the deformed plate is given by

$$V_{deformed} = 2\pi r\delta H \qquad \text{(eq. 2.70)}$$

Considering the volume of the deformed plate to be constant and unchanged from its initial volume ($V_{initial} = V_{deformed}$). The following relationship is obtained

$$\frac{\pi}{4} D^2 H_0 = 2\pi r H \delta \qquad \text{(eq. 2.71)}$$

Where, H is the final thickness of the plate after deformation, which is uniform according to the basic simplified model. Using equation (2.68) and rearranging equation (2.71) yields

$$\frac{H}{H_o} = \frac{D^2}{4\delta^2 + D^2} \qquad \text{(eq. 2.72)}$$

The thickness strain is given by equation (2.73)

$$\varepsilon_H = \ln\left(\frac{H}{H_o}\right) = \ln\left(\frac{D^2}{4\delta^2 + D^2}\right) = -\ln\left[1 + 4\left(\frac{\delta}{D}\right)^2\right] \quad \text{(eq. 2.73)}$$

From incompressibility of the deformed plate

$$\varepsilon_H + \varepsilon_r + \varepsilon_\theta = 0 \quad \text{(eq. 2.74)}$$

Where ε_r – radial strain, ε_θ – circumferential strain

Based on the assumption of uniform surface strain

$$\varepsilon_r = \varepsilon_\theta \quad \text{(eq. 2.75)}$$

Hence equation (2.74) gives

$$\varepsilon_r = \varepsilon_\theta = -\frac{1}{2}\varepsilon_H \quad \text{(eq. 2.76)}$$

Substituting equation (2.76) in the effective strain equation (2.62)

$$\varepsilon_{eff} = -\varepsilon_H \left(= 2\varepsilon_r = 2\varepsilon_\theta\right) \quad \text{(eq. 2.77)}$$

Thus from equation (2.73)

$$\varepsilon_{eff} = \ln\left[1 + 4\left(\frac{\delta}{D}\right)^2\right] \quad \text{(eq. 2.78)}$$

The strain energy per unit volume, U_{strain}, is obtained by substituting equation (2.78) into (2.64)

$$U_{strain} = \frac{K}{n+1}\left\{\ln\left[1 + 4\left(\frac{\delta}{D}\right)^2\right]\right\}^{n+1} \quad \text{(eq. 2.79)}$$

Therefore the total strain energy for deformation is given by

$$U_{def} = volume_{plate} \times U_{strain} \quad \text{(eq. 2.80)}$$

Hence

$$U_{def} = \frac{\pi}{4} D^2 H_o \frac{K}{n+1}\left\{\ln\left[1 + 4\left(\frac{\delta}{D}\right)^2\right]\right\}^{n+1} \quad \text{(eq. 2.81)}$$

Kosing and Skews [21], report good correlation between predicted mid-point deflections using equation (2.81) and experimental results on copper plates loaded using a liquid shock tube.

If, instead of strain hardening effects, the assumption of constant yield stress, σ_o, the strain energy in the dome shaped plate is obtained by substituting equation 2.78 into equation 2.65,

$$U_{def} = \frac{\pi}{4} D^2 H_o \sigma_o \ln\left[1 + 4\left(\frac{\delta}{D}\right)^2\right] \qquad \text{(eq. 2.82)}$$

2.5.3.1 *Duffey, [5, 36], energy analysis method for rigid-plastic behaviour of plates*

The deformation energy analysis is sensitive to the final deflection shape assumed. For the analysis of experimental results herein the shape function used is given by equation (2.83) to describe the plate deformations. An illustration of the shape of the plate after deformation is shown in Figure 2.55.

$$w = \delta \cos\left(\frac{\pi r}{2R}\right) \qquad \text{(eq. 2.83)}$$

Where, r – Change in plate radius, R – Plate radius, w – Change in plate deflection, δ – Final mid-point deflection

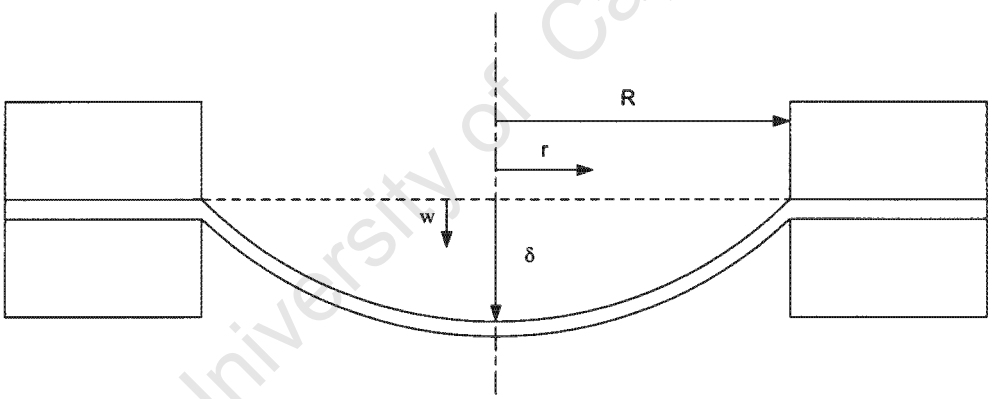


Figure 2.55: Clamped circular plate after deformation

The deformation energy is given by,

$$U_{def} = \pi H \int_0^R \frac{\sigma_0^1}{\left(1 - \nu + \nu^2\right)^{1/2}} \left(\frac{\partial w}{\partial r}\right)^2 r dr \qquad \text{(eq. 2.84)}$$

Where, w is the shape function given by equation (2.83), δ – Mid-point deflection, ν – Poisson's ratio, σ_o^1 – Dynamic yield stress, H – Plate thickness

Substituting equation (2.83) into (2.84) and integrating gives

$$U_{def} = \frac{\pi^3 H \sigma_0^1 \delta^2}{4\left(1 - v + v^2\right)^{1/2}} \left(\frac{1}{4} + \frac{1}{\pi^2}\right) \quad \text{(eq. 2.85)}$$

The mild steel used in experiments is sensitive to strain rate. The material under goes strain hardening during blast loading and therefore as strain rate increases, the value of the dynamic yield stress increases. Teeling-Smith and Nurick [5] use dynamic yield stress calculated using an iterative procedure (equation (2.86)) proposed by Symonds and Wierzbicki [37]

$$\frac{0.05365 I^2}{R^5 H^2 \sqrt{\rho^3 \sigma_o^1}} = 40.4 \left[\frac{\sigma_0^1}{\sigma_0} - 1\right]^5 \quad \text{(eq. 2.86)}$$

Where, R – plate radius, H – plate thickness, I – impulse, ρ – plate density,
σ_o – static yield stress and σ_o^1 – dynamic yield stress
A simple energy balance is used to define Mode I type failure with large inelastic deformation [5].

$$E_{input} = U_{def} \quad \text{(eq. 2.87)}$$

2.5.3.2 *Input energy for impulsively loaded structures*

The input energy can be simply related to measured impulse using the following methodology for structures with natural period greater than duration of the load. The principle behind this methodology is to acknowledge that when an impulse is delivered to a structure it produces an instantaneous velocity change. As a result the structure gains kinetic energy which is converted to strain energy, (Smith and Hetherington [18]).
Input energy = kinetic energy applied on plate

$$E_{input} = \frac{1}{2} m v^2 \quad \text{(eq. 2.88)}$$

Where, m – Plate mass, v – velocity
Impulse can be written as

$$I = mv \quad \text{(eq. 2.89)}$$

Rewriting equation (2.89) and substituting into equation (2.88)

$$v = \frac{I}{m} \quad \text{(eq. 2.90)}$$

$$E_{input} = \frac{I^2}{2m} \quad \text{(eq. 2.91)}$$

Where, mass = plate density x plate volume

$$m = \pi R^2 H \rho \qquad \text{(eq. 2.92)}$$

Therefore input energy is given by

$$E_{input} = \frac{I^2}{2\pi R^2 H \rho} \qquad \text{(eq. 2.93)}$$

3 Experimental details

This chapter describes the details of blast loading experiments on clamped circular plates manufactured from mild steel.

3.1 Experimental procedure

Disc shaped plastic explosive of radius, R_p, and thickness, h, is used to impart a blast load onto the loaded side of circular test plates. The impulse is measured using a ballistic pendulum. This experimental method has been widely reported by Nurick et al. [6 - 8] and has proven to be reliable and reproducible.

The experiments described herein differ from previous experiments as mild steel tubes of different lengths are used to vary the stand off distance between the explosive load and test plate as shown in Figure 3.1. The aim of these experiments is to understand the influence of varying stand off distances on plate response.

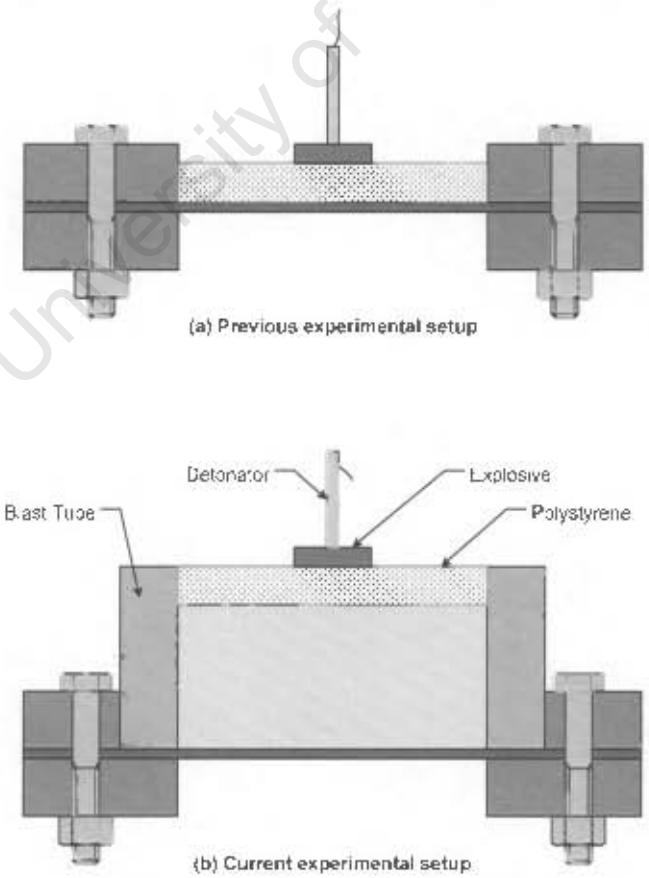


Figure 3.1: Schematic diagram showing blast loading of circular mild steel plates (a) experimental setup used previously and (b) current setup

3.1.1 Experimental arrangement

The apparatus used in these experiments are listed below,

- Ballistic Pendulum – used to measure the applied impulse
- Tubes – 106mm internal diameter used to vary the stand off distance
- Mild steel test specimens, nominal thickness of 1.9mm

3.1.2 Ballistic pendulum

The ballistic pendulum is used to measure the impulse applied to the test plate. The ballistic pendulum consists of a steel I-beam suspended on four spring steel cables. The spring steel cables are attached to the I-beam of the ballistic pendulum by four adjustable screws. The pendulum is levelled by adjusting the screws and verified using a spirit-level. Counter-balancing masses are attached at one end as shown in Figures 3.2 and 3.3. The counter balancing masses are used to counter the mass of the test rig attached on the other end so as to ensure that all four spring steel cables carry the same load. Hence, the impulse generated by the explosion is transmitted through the centroid of the pendulum. A soft tipped recording pen is attached to the pendulum on the same side as the counter balancing masses as shown in Figure 3.3, to record the oscillation amplitude of the pendulum on a sheet of tracing paper. The oscillation relates directly to the impulse generated by the explosion and transmitted to the test specimen. A photograph of the complete experimental set up ready for testing is shown in Figure 3.4. The methodology for calculating the impulse imparted on to the plate by the explosive load is given in Appendix A.

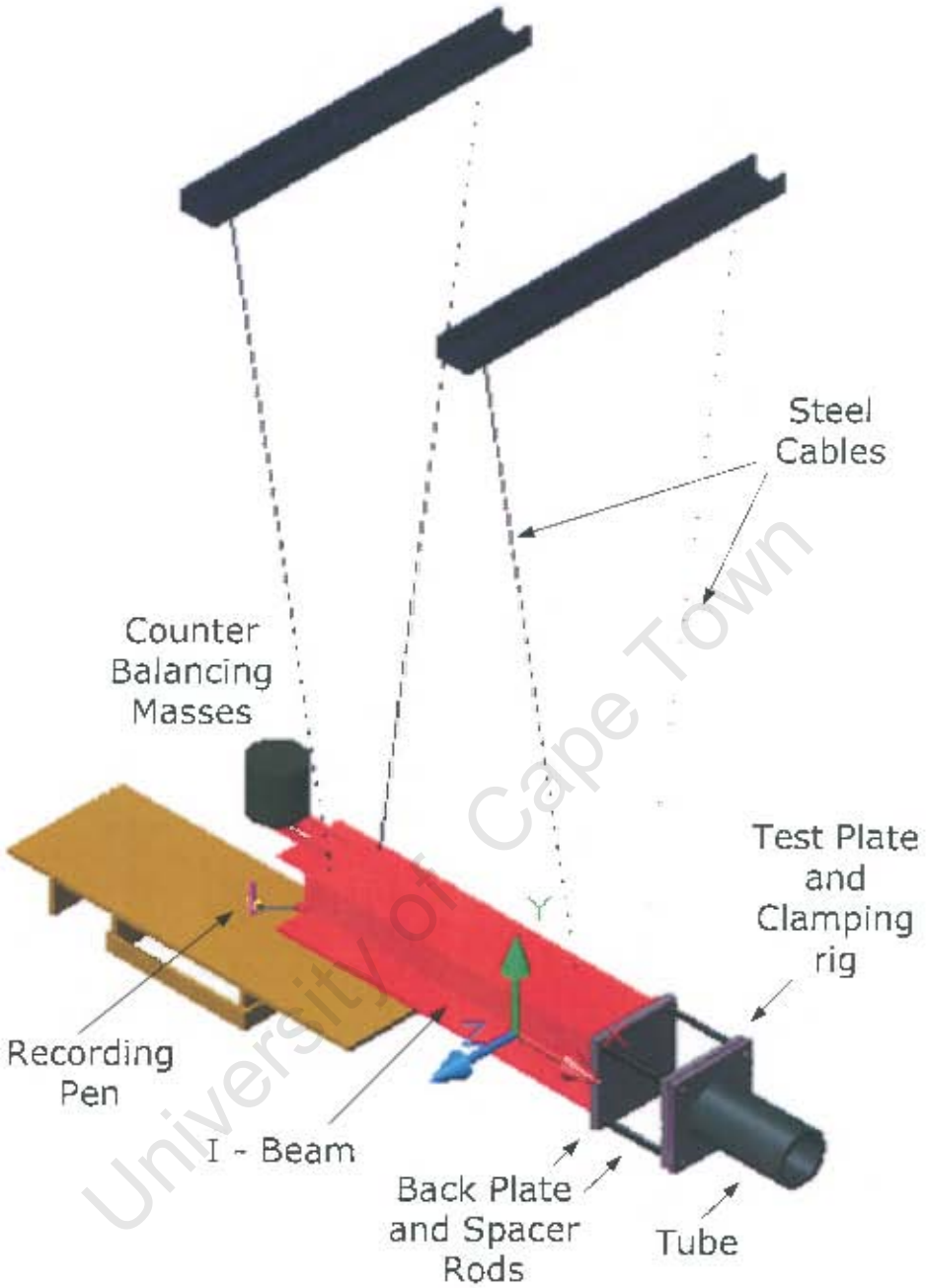


Figure 3.2: 3D rendered view of the ballistic pendulum

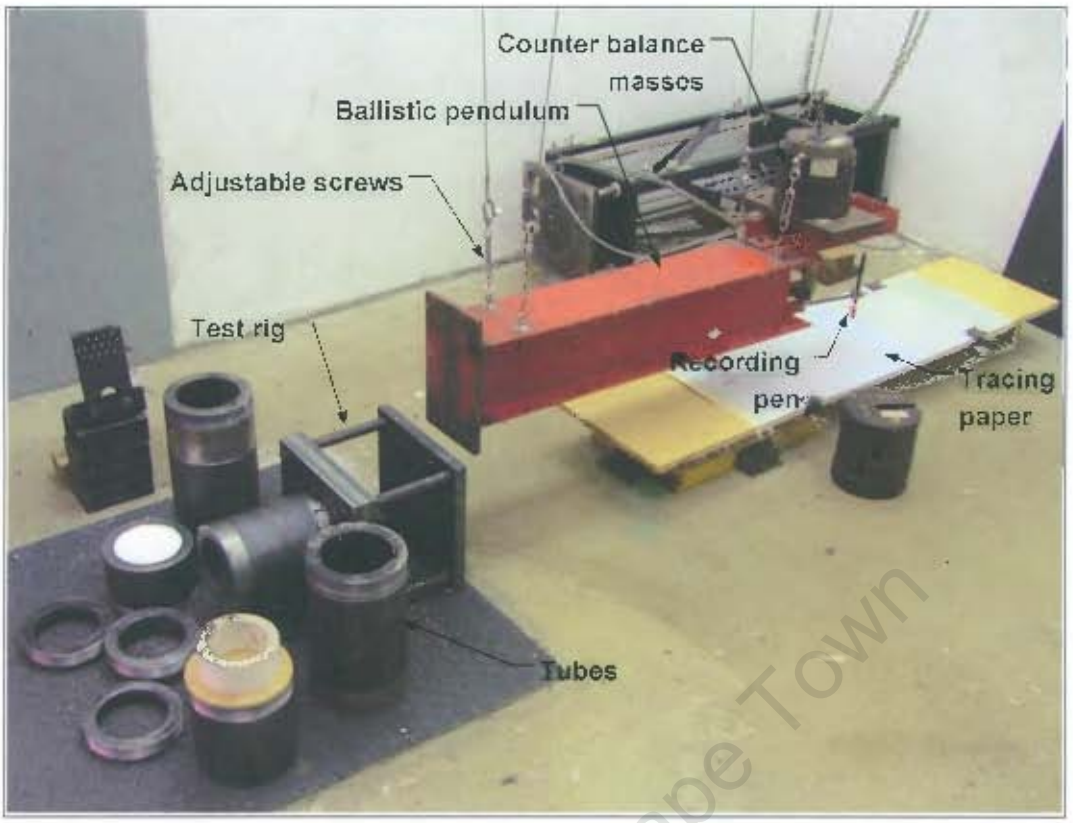


Figure 3.3: Photograph of the test rig with different length tubes and ballistic pendulum

Figure 3.4: Photograph of test rig attached to the ballistic pendulum

3.1.3 Test rig and specimen

The test rig consists of two (244mm x 244mm) clamping frames made from 20mm thick mild steel. A tube of required length selected from the range shown in Figure 3.5 is screwed onto one of the clamping plates and the other clamping plate has a hole machined to 106mm diameter, the same as the internal diameter of the tube as shown in Figure 3.6. The test specimen is sandwiched between the two clamping plates.

The test rig is attached to the ballistic pendulum using four connecting spacer rods. The spacer rods allow the plate to deform without coming in contact with the I-beam of the ballistic pendulum.

Tube specification:

- Internal diameter – 106mm
- Outer diameter – 150mm
- Thickness – 22mm
- Lengths – 25mm, 30mm, 40mm, 50mm, 75mm, 100mm, 150mm, 200mm, 250mm and 300mm

Figure 3.5: Photograph of mild steel tubes used in the experiments

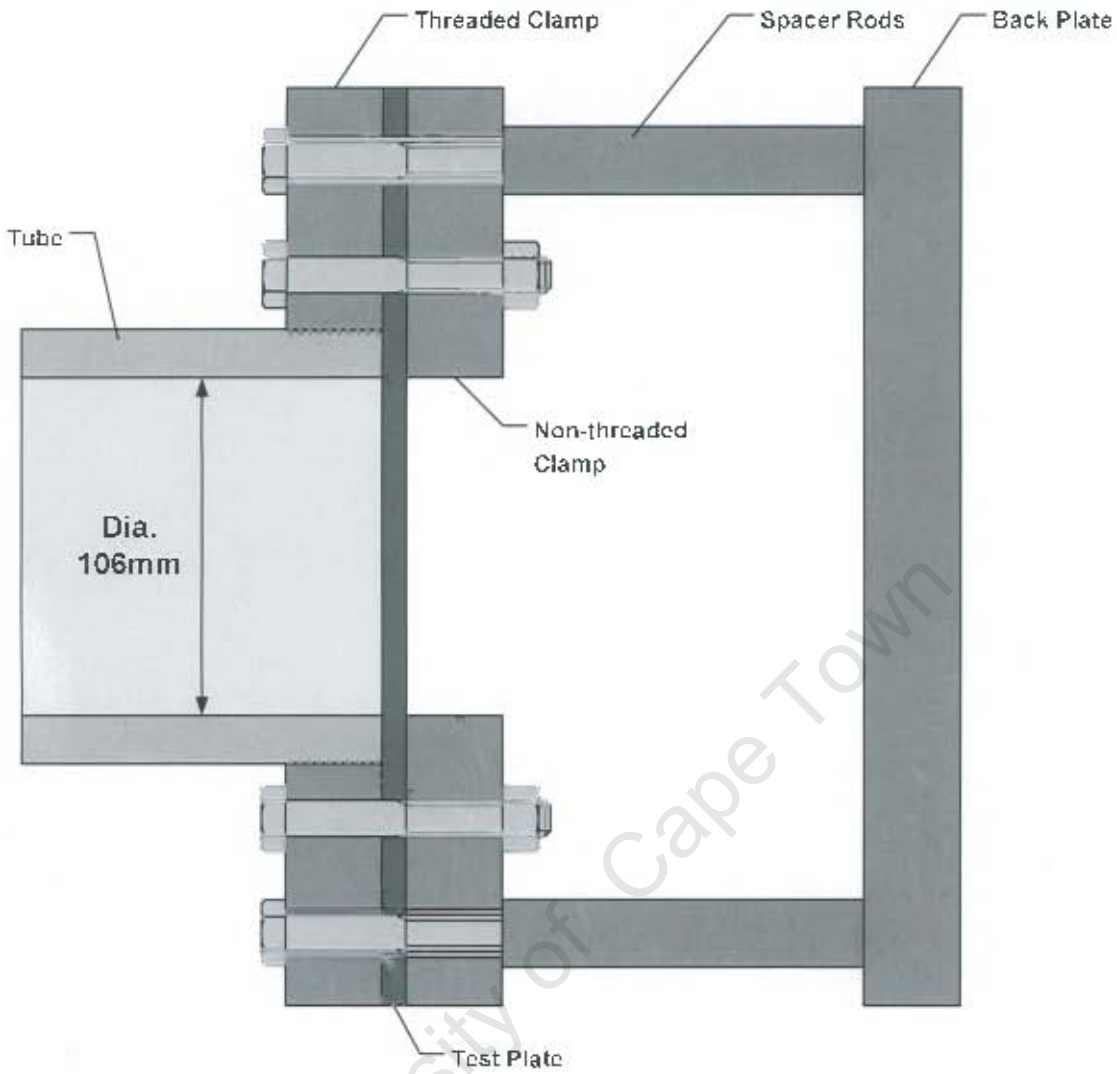


Figure 3.6: Schematic of the experimental test rig

The test specimen is cut to the same outer dimensions as the clamping plates (244mm x 244m) and with nominal plate thickness of 1.9mm. The test specimens are laser cut from three sheets of mild steel.

3.2 Test Specimen material properties

A summary of material properties for the mild steel plates used is presented in Table 3.1. Standard uni-axial flat tensile test specimens are cut from the three mild steel sheets used, labelled A, B and C. The gauge length is 40mm, due to limitation of the extensiometer fitted on the Zwick tensile test machine, which has a maximum extension of 60mm. Three strain rates were selected ($8.33x10^{-4}$, $4.17x10^{-3}$ and $2.08x10^{-2}s^{-1}$) and two specimens from each sheet were tested at the same speed. The results are shown in Table 3.2. The graphs of engineering stress versus engineering strain for the different strain rates are shown in Figures 3.7 – 3.9. The graphs of stress versus strain for each sheet at different strain rates are shown in Figures 3.10 – 3.12. Assuming the mild steel plates to be rigid-viscoplastic, static yield stresses were calculated using the Cowper-Symonds relation:

$$\frac{\sigma_0^1}{\sigma_o} = 1 + \left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]^{1/\eta} \qquad \text{(eq. 3.1)}$$

Where, σ_0^1 - Dynamic yield stress, σ_0 - Static yield stress, $\dot{\varepsilon}$ - Strain rate, $\dot{\varepsilon}_0$ and $\eta$are material constants

Density of mild steel is determined by weighing the test plates and calculating the plate volume.

Table 3.1: Summary of material properties of mild steel test specimens

Density	$7691kgm^{-3}$
$\dot{\varepsilon}_0$ [34]	40.4
η [34]	5
Poisson's ratio	0.33
Average Static Yield Stress	240MPa
K (strength coefficient)	591.23MPa
n (strain hardening exponent)	0.21
Average % Uni-axial strain at failure	41.03

Table 3.2: Uniaxial tensile test results

Specimen number	Specimen thickness mm	Specimen width mm	Test speed mm/min	Strain rate	Dynamic yield stress MPa	Static yield stress MPa	% Strain at failure
A2	1.91	12.50	2	0.00083	266	238	43.0
A10	1.91	12.50	2	0.00083	266	238	44.4
A3	1.90	12.50	10	0.00417	283	244	40.4
A4	1.90	12.55	10	0.00417	292	252	41.9
A5	1.91	12.50	50	0.02083	281	230	40.5
A6	1.91	12.50	50	0.02083	275	225	39.8
					Average	238	41.7

Specimen number	Specimen thickness mm	Specimen width mm	Test speed mm/min	Strain rate	Dynamic yield stress MPa	Static yield stress MPa	% Strain at failure
B1	1.90	12.50	2	0.00083	268	240	42.8
B2	1.91	12.49	2	0.00083	272	244	43.2
B3	1.90	12.52	10	0.00417	291	251	39.4
B4	1.90	12.51	10	0.00417	271	234	40.3
B5	1.90	12.50	50	0.02083	282	231	39.5
B6	1.91	12.50	50	0.02083	299	245	38.5
					Average	241	40.6

Specimen number	Specimen thickness mm	Specimen width mm	Test speed mm/min	Strain rate	Dynamic yield stress MPa	Static yield stress MPa	% Strain at failure
C2	1.91	12.52	2	0.00083	268	240	41.8
C3	1.92	12.50	2	0.00083	270	242	42.6
C4	1.91	12.56	10	0.00417	292	252	39.7
C5	1.91	12.52	10	0.00417	283	244	39.7
C6	1.91	12.50	50	0.02083	291	239	40.9
C7	1.91	12.50	50	0.02083	283	232	40.0
					Average	241	40.8

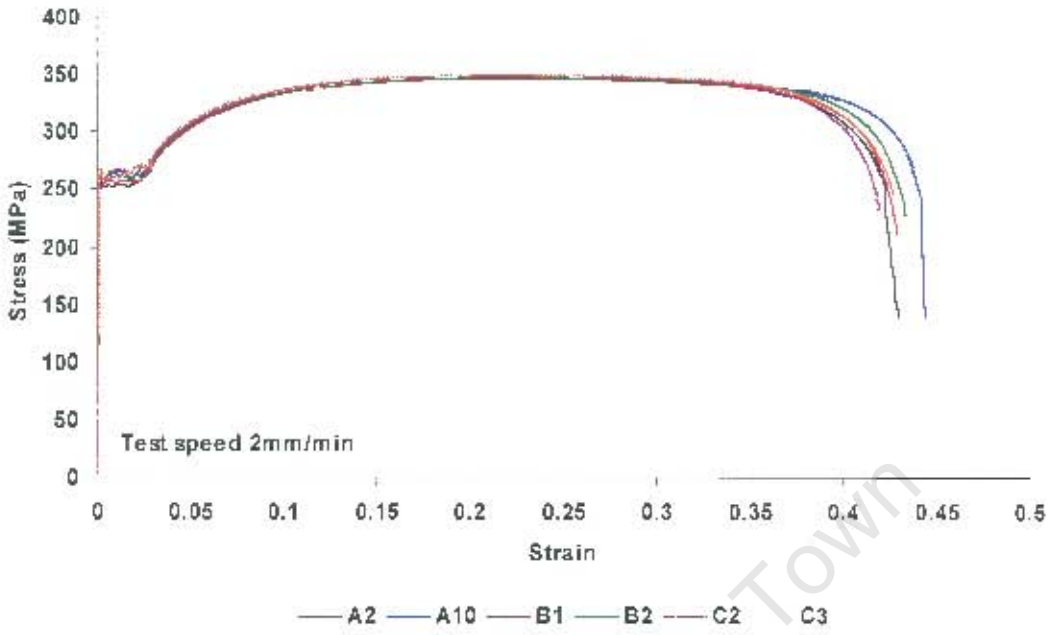


Figure 3.7: Graph of Stress versus Strain for strain rate $8.33 \times 10^{-4} s^{-1}$

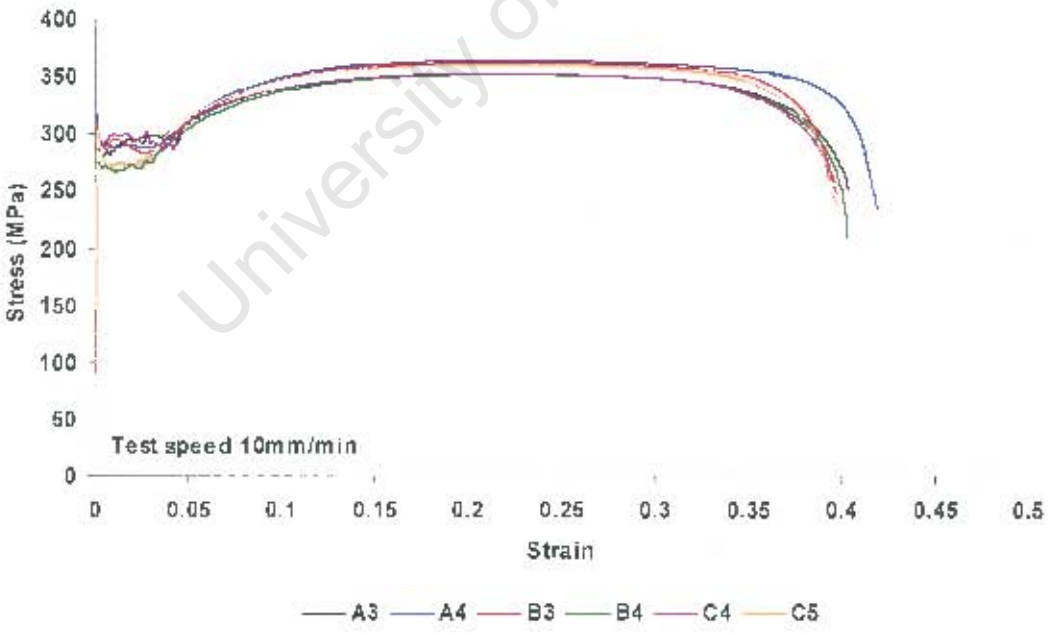


Figure 3.8: Graph of Stress versus Strain for strain rate $4.17 \times 10^{-3} s^{-1}$

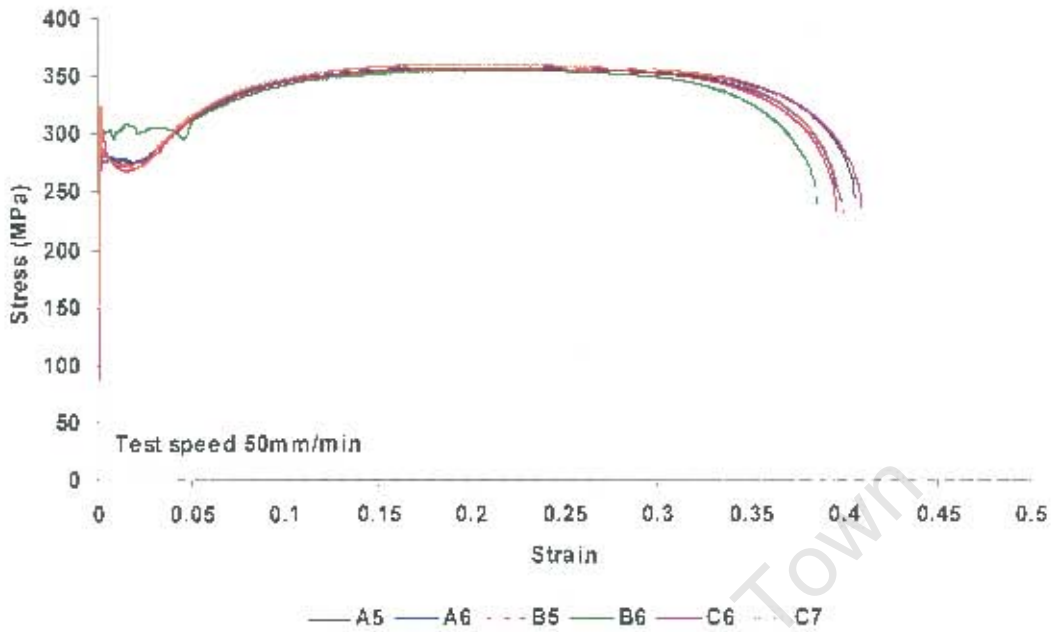


Figure 3.9: Graph of Stress versus Strain for strain rate $2.08 \times 10^{-2} s^{-1}$

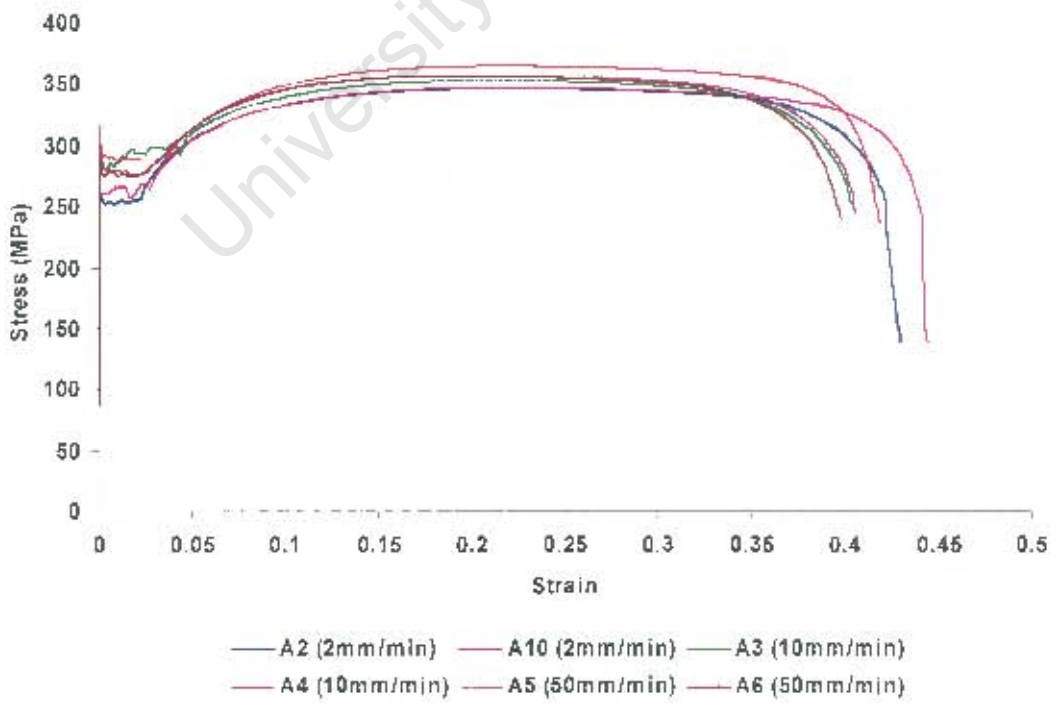


Figure 3.10: Graph of Stress versus Strain at different cross-head speeds for Sheet A

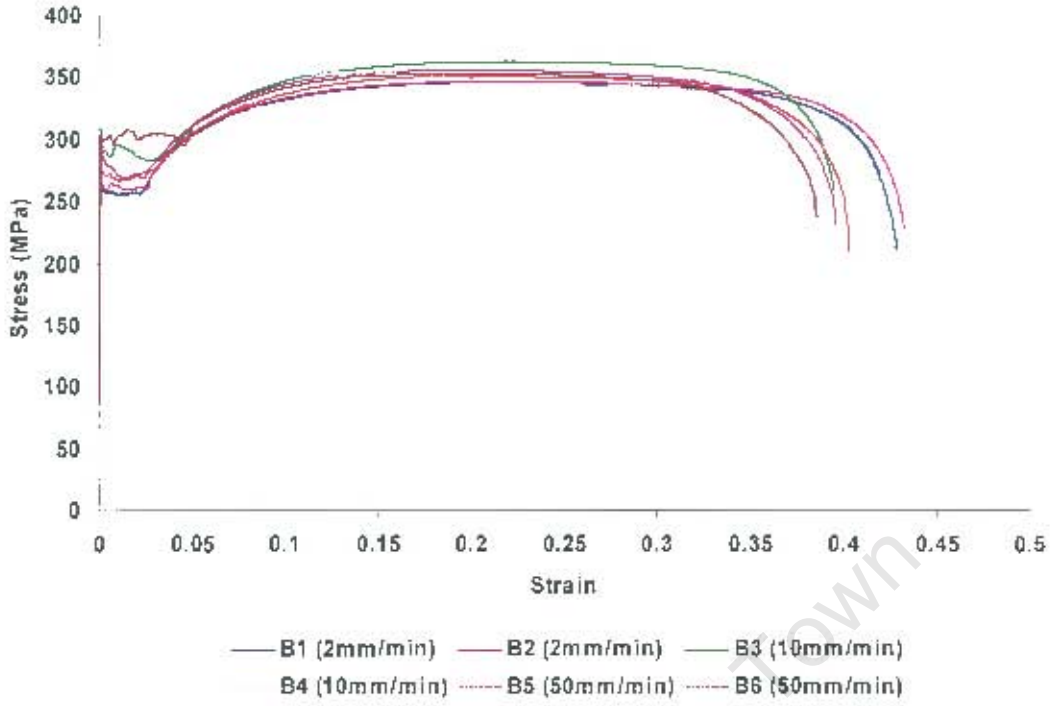


Figure 3.11: Graph of Stress versus Strain at different cross-head speeds for Sheet B

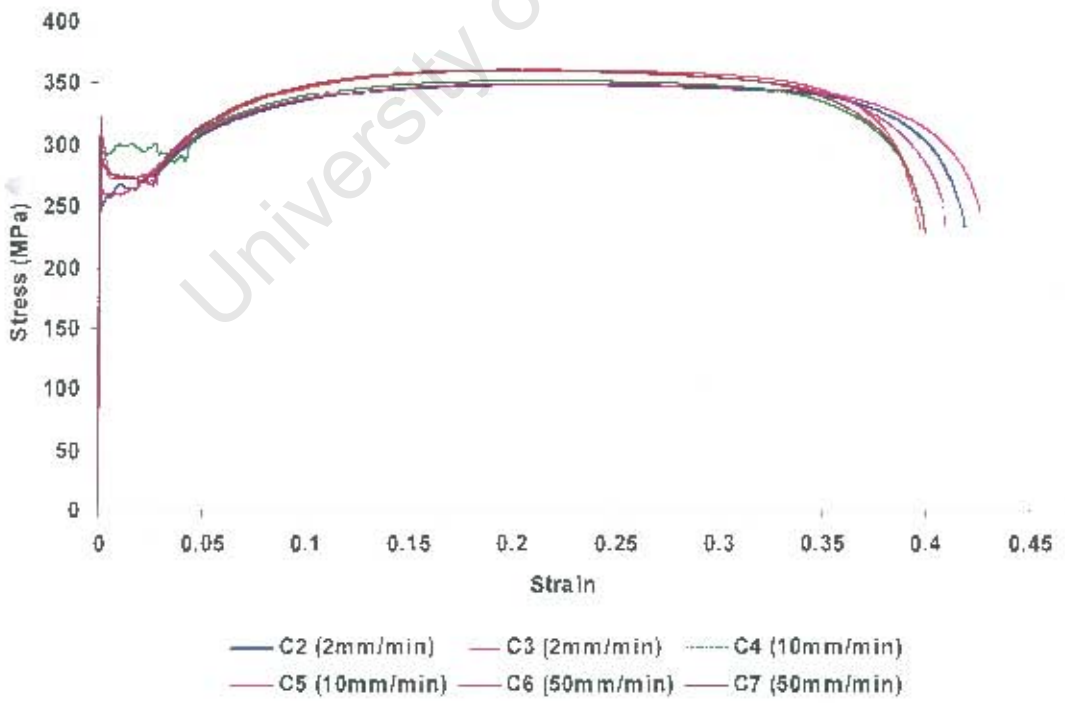


Figure 3.12: Graph of Stress versus Strain at different cross-head speeds for Sheet C

3.3 Blast loading

Plastic explosive PE4 is used to provide the blast load on test specimens. PE4 is a combination of RDX and Lithium grease (Wharton et al [38]).

Table 3.3: Composition and material characteristics of PE4, [38]

RDX and Lithium grease	88% RDX and 12% Lithium grease
Density	1.6 (gcm^{-3})
$TNT_{equivalent}$	130% (by ballistic mortar tests)
Detonation velocity	8200 (ms^{-1})

The PE4 is shaped into a disc of diameter 34mm and placed onto a 13mm thick polystyrene pad as shown in Figure 3.13. The diameter of the pad is identical to the diameter (110mm) of the recess machined at end of the tubes. A 1g leader of explosive is used to attach the detonator to the main charge, as shown in Figure 3.14. Thus the total mass of explosive is the sum of the disc and the 1g leader. The inclusive charge masses used in this investigation are 4g, 5g, 7g, 9g, 11g, 13g and 15g. The different loading scenarios implemented to ascertain the possible effects of using the polystyrene pad as a stand-off buffer to prevent spalling is discussed in detail in Section 3.3.1.

A summary of experimental details is given in Table 3.4.

Table 3.4: Summary of experimental details

Test parameters	Details
Plate thickness	1.9mm
Plate diameter	106mm
Stand-off distance (tube lengths)	25mm, 30mm, 40mm, 50mm, 75mm, 100mm, 150mm, 200mm, 250mm and 300mm
Charge diameter	34mm
Charge mass	4g, 5g, 7g, 9g, 11g, 13g and 15g

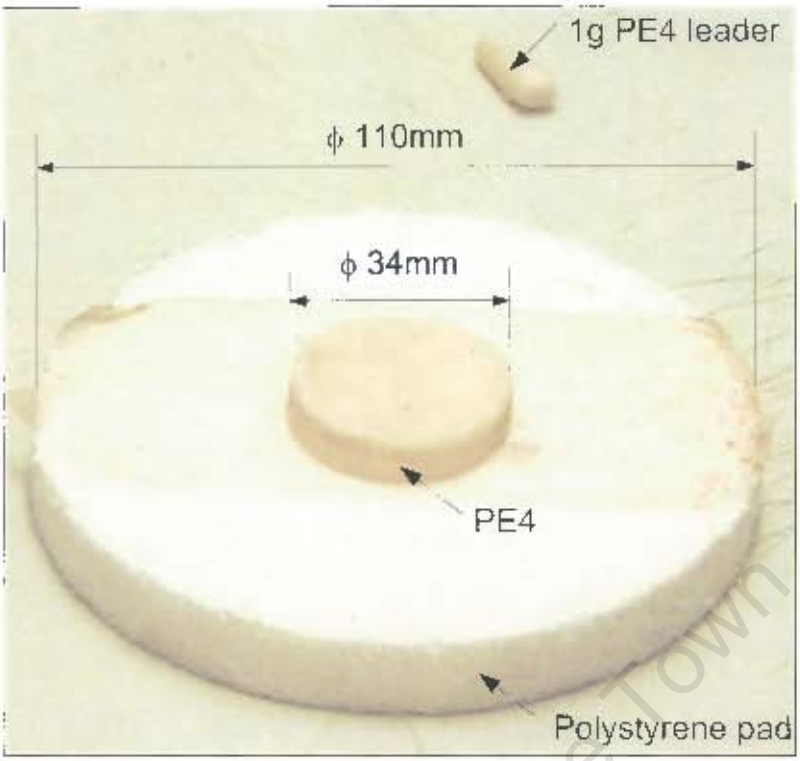


Figure 3.13: Photograph of disc shaped PE4 explosive of diameter 34mm attached to a circular polystyrene pad of diameter 110mm and thickness of 13mm

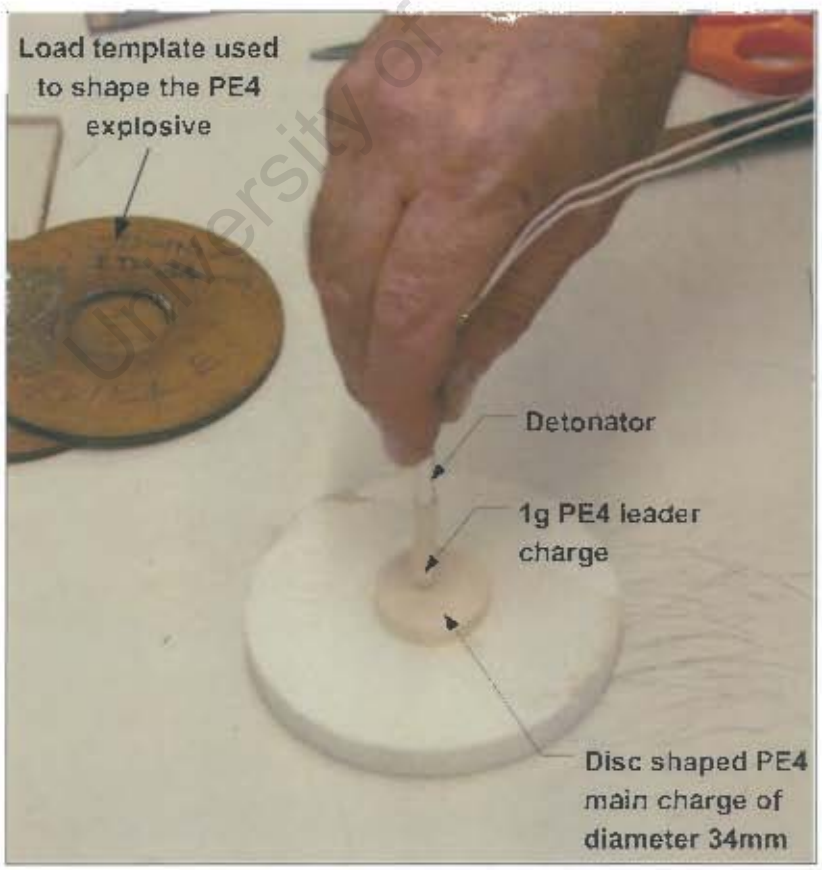


Figure 3.14: Photograph of disc shaped PE4 explosive with 1g leader attached to the detonator

3.3.1 Different blast loading conditions

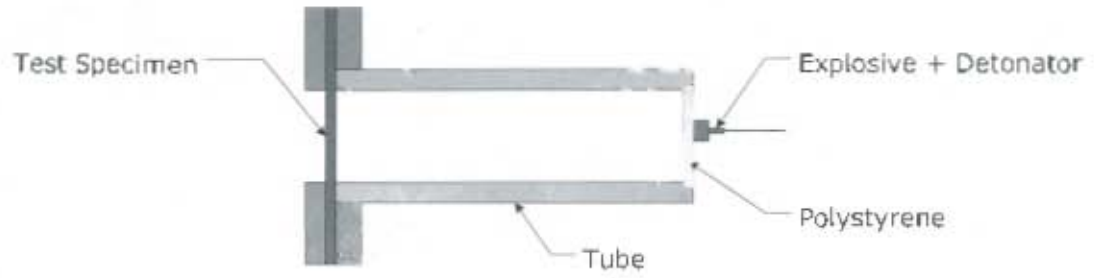
Nurick and Martin [2] report on various materials (for example, sponge rubber and neoprene) used to separate the explosive charge and the test plate to prevent spallation. They also report an experimental investigation conducted by Jones, Uran and Tekin (1970) on fully clamped rectangular plates. A significant result of this work was that the type of attenuator, i.e. foam or neoprene, did not appear to influence the outcome of the tests, except that the impulsive velocity varied according to the attenuator used [2]. Langdon [39] suggests research into the possible effects of using polystyrene to separate the explosive and plate on measured impulse and plate deformation. Hence different loading conditions are used in this investigation as shown in Figure 3.15 and classified as follows,

- ***Loading condition 1 (LC-1)*** – The plastic explosive is attached to a 13mm thick polystyrene pad using a strip of double sided tape and the pad is pushed into place on the end of a tube. Stand off distance is varied using different lengths of tube. This arrangement is shown in Figure 3.15(a).

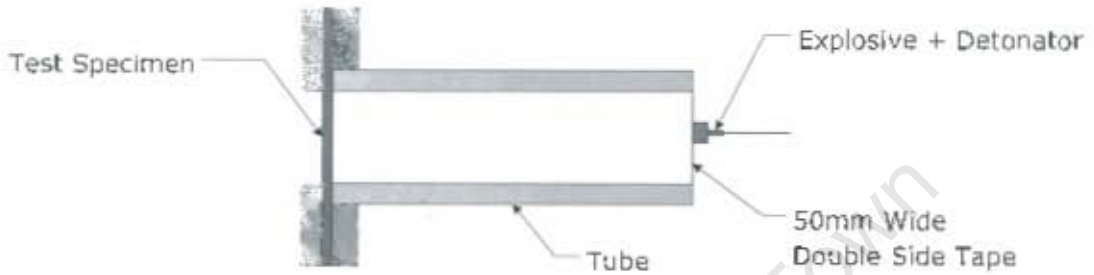
- ***Loading condition 2 (LC-2)*** – Double sided tape is used to secure the plastic explosive at one end of the tube, as shown in Figure 3.15(b).
  Note: *No polystyrene is used.*

- ***Loading condition 3 (LC-3)*** – Double sided tape is used to secure the plastic explosive at one end of the tube. A 13mm polystyrene pad is placed directly against the test specimen as shown in Figure 3.15(c).

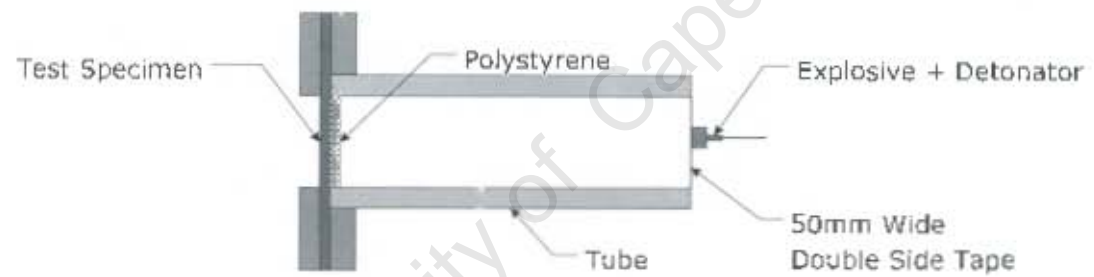
- ***Loading condition 4 (LC-4)*** – this method has been widely used by Nurick et al [6 - 8]. In this case the plastic explosive is mounted on the polystyrene pad using double sided tape and placed directly against the test specimen as shown in Figure 3.15(d).



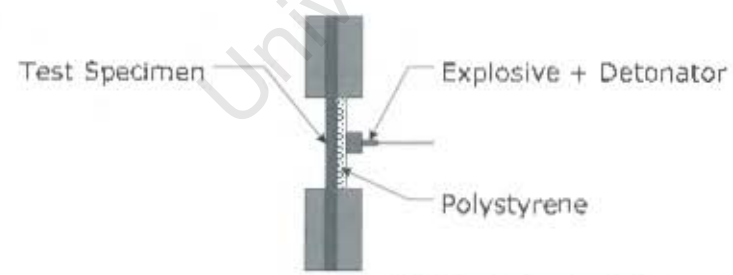
(a) Loading Condition 1 (LC-1)



(b) Loading Condition 2 (LC-2)



(c) Loading Condition 3 (LC-3)



(d) Loading Condition 4 (LC-4)

Figure 3.15: Different loading conditions used in experiments

3.4 Experimental measurements

For the experiments the following measurements are required and measured:

- The impulse imparted on to each test specimen measured from the pendulum displacement
- Mid-point deflection of each test specimen is measured using a digital height gauge as shown in Figure 3.16

Figure 3.16: Photograph of height gauge used to measure the final mid-point deflection of a test specimen after a test

4 Experimental results

This chapter describes the results and observations from blast tests on clamped circular plates at varying stand-off distances for loading conditions LC-1, LC-2, LC-3 and LC-4. The measured test data is presented in Section 4.4. Chapter 5 discusses the results in more detail.

4.1 General plate deformation

In most cases Mode I type failure on the plates (large inelastic deformation) was observed. The plate profiles differ according to the distance between the plastic explosive and the test specimens. In cases with stand-off distances ranging from 100mm to 300mm, the plate profile resembled a uniform dome shape as shown in Figures 4.1. In cases of shorter stand-off distances ranging from 13mm to 40mm the plate profile resembled a smaller inner dome atop a larger global dome as shown in Figure 4.2.

Figure 4.1: Photograph of plate profile showing large global dome. Plate number NJ230405b, I = 12.03Ns, S = 150mm

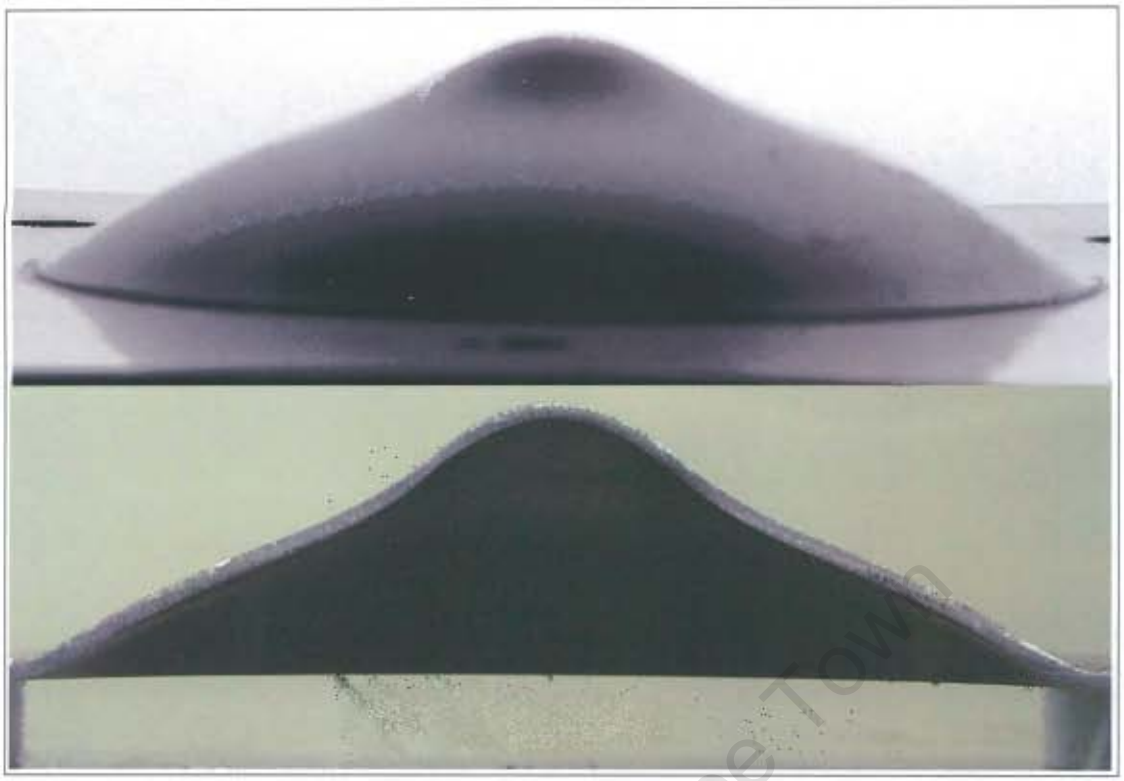


Figure 4.2: Photograph of typical plate profile for smaller stand off distances (13mm to 40mm) Plate number NJ250405c, I =12.44Ns, S = 13mm

The change in plate profile at different stand-off distances is shown in Figures 4.3 – 4.5 for charge masses 4g, 7g and 9g respectively. The plate profiles change from dish shape (large global dome) at stand-off distances ranging from 300mm to 100mm. An inner dome atop a global dome is observed for stand-off distances ranging from 40mm to 13mm. The plate profile at stand-off distance 50mm and 75mm exhibit an increase in deformation near the boundary, but the deformation does not show an inner dome near the centre of the plate. The measured mid point deflections for stand off distances 75mm, 100mm, 150mm, 200mm, 250mm and 300mm show little variation. This is shown in Figures 4.3 – 4.5 by the closed packed nature of the bottom five plates.

Figure 4.3: Photograph of sequential layout of test specimens for increasing stand-off distance for constant charge mass, 5g
(Plate numbers top to bottom - NJ250405b, NJ160405g, NJ160405a, NJ150405a, NJ090405a, NJ020705b, NJ080405a, NJ230405c, NJ050405a, NJ290305f and NJ210405a)

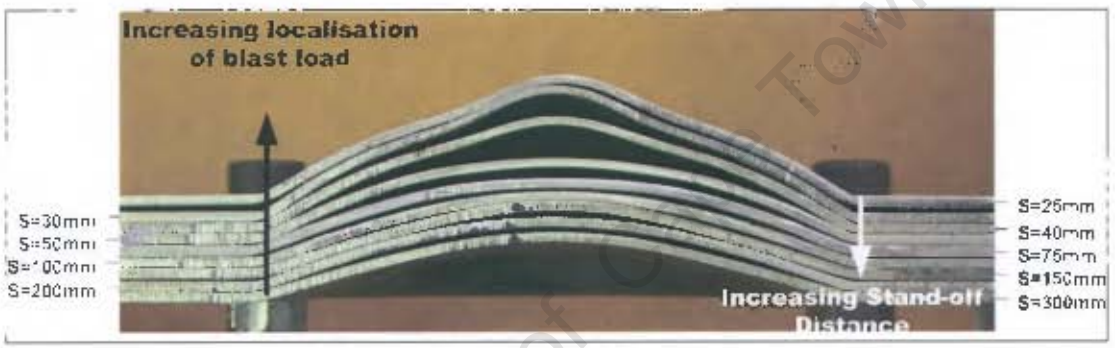


Figure 4.4: Sequential layout of test specimens for increasing stand-off distance for constant charge mass, 7g
(Plate numbers top to bottom - NJ160405h, NJ150405b, NJ090405b, NJ020705c, NJ080405b, NJ230405d, NJ050405b and NJ210405d)

Figure 4.5: Sequential layout of test specimens for increasing stand-off distance for constant charge mass, 9g
(Plate numbers top to bottom - NJ160405i, NJ160405d, NJ150405c, NJ040705a, NJ080405c, NJ060405c, NJ050405c and NJ310305c)

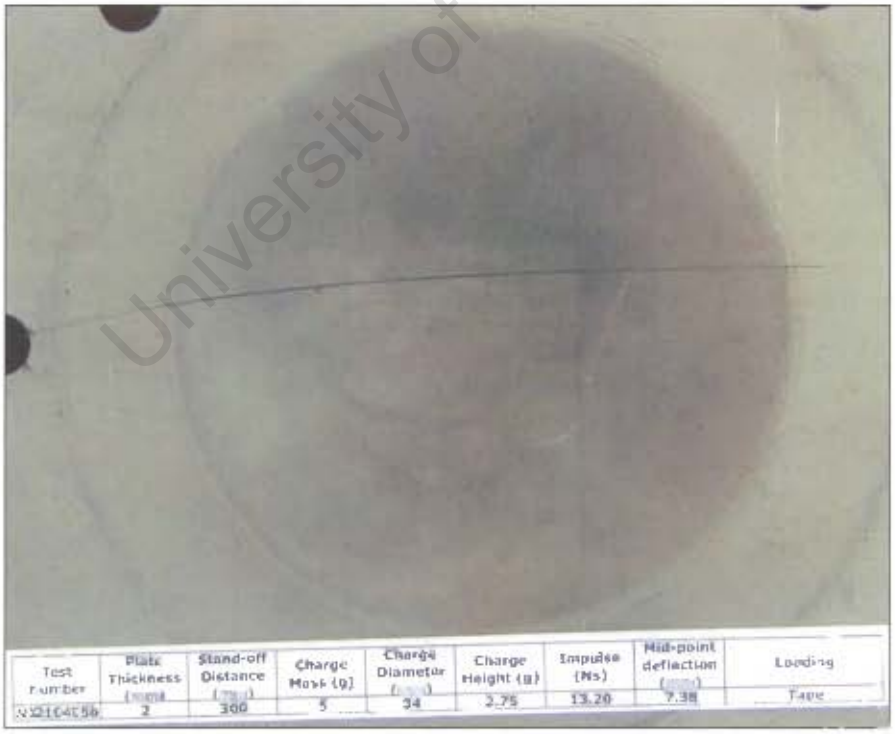
4.2 Effect of different loading conditions

Polystyrene has been used extensively in experiments reported by Nurick et al [2 – 8, 25, 27 – 31]. It is used primarily as a stand-off buffer to prevent spalling. Nurick and Martin [2] report an experimental investigation conducted by Jones et al (1970) on rectangular plates subjected to blast loading. The results indicated that, the type of stand-off buffer used (for example, neoprene or foam) does not appear to influence the outcome of the tests. However, it was deemed necessary to ascertain if polystyrene had any observable effect on plate deformation and impulse [39] using the different loading conditions outlined in Section 3.3.1.

Figures 4.6, 4.7 and 4.8 show the loaded side of the plates for load conditions LC-1, LC-2 and LC-3 respectively. The reader is reminded of the different loading conditions as shown in Figure 3.15. The loaded side of a test plate subjected to load condition LC-1 shows an even coating of black soot on the surface of the plate as shown in Figure 4.6. The charge mass was kept constant and the polystyrene was replaced with double sided tape (LC-2). The loaded side had significantly less black soot as seen for the previous load condition (LC-1). The plate surface was visible and covered with a thin coating of semi-transparent soot which can be easily wiped away as shown in Figure 4.7. Following the test pattern described previously, charge mass was maintained and a 13mm thick polystyrene pad was placed directly against the plate. Thus the explosive charge was separated from the polystyrene by the distance of the tube (LC-3). After the test, residue of the polystyrene was visible on the loaded side of the test plate as shown in Figure 4.8 and a close up of the residue is shown in Figure 4.9. The cross-sectional view of plates subjected to LC-1, LC-2 and LC-3 for charge mass of 5g and 7g are shown in Figures 4.10 and 4.11 respectively.

Test Number	Plate Thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (g)	Impulse (Ns)	Mid-point deflection (mm)	Loading
NJ210405a	2	300	5	34	2.75	13.32	7.01	Normal

Figure 4.6: Photograph of black soot observed for test plate subjected to load condition LC-1
Test plate Number NJ210405a, S = 300mm, I = 13.32Ns and Mid-point deflection = 7.01mm



Test Number	Plate Thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (g)	Impulse (Ns)	Mid-point deflection (mm)	Loading
NJ210405b	2	300	5	34	2.75	13.20	7.38	Tape

Figure 4.7: Photograph of translucent soot observed for test plate subjected to load condition LC-2
Test plate Number NJ210405b, S=300mm, I=13.20Ns and Mid-point deflection = 7.38mm

Test Number	Plate thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (g)	Impulse (Ns)	Mid-point deflection (mm)	Loading
NJ210405c	2	300	6	34	2.75	12.24	7.87	Tape+poly @ Plate

Figure 4.8: Photograph of polystyrene residue visible for test plate subjected to load condition LC-3
Test plate Number NJ210405c, S = 300mm, I = 12.24Ns and Mid-point deflection = 7.87mm

Figure 4.9: Photograph showing a close up view of the polystyrene residue visible for test plate (NJ210405c) subjected to load condition LC-3

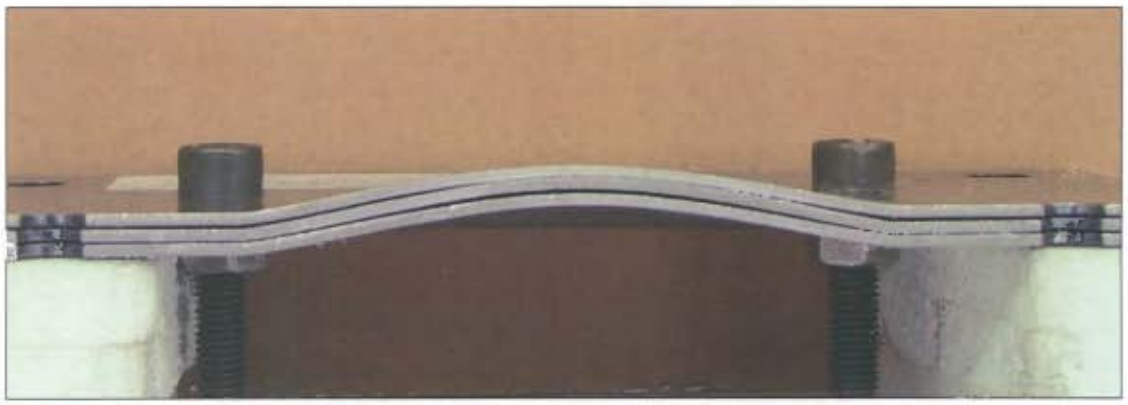


Figure 4.10: Photograph of plate profile for test plate subjected to same charge mass (5g) but different load conditions (LC-1, LC-2 and LC-3) Test plate Numbers, NJ210405a, NJ210405b, NJ210405c

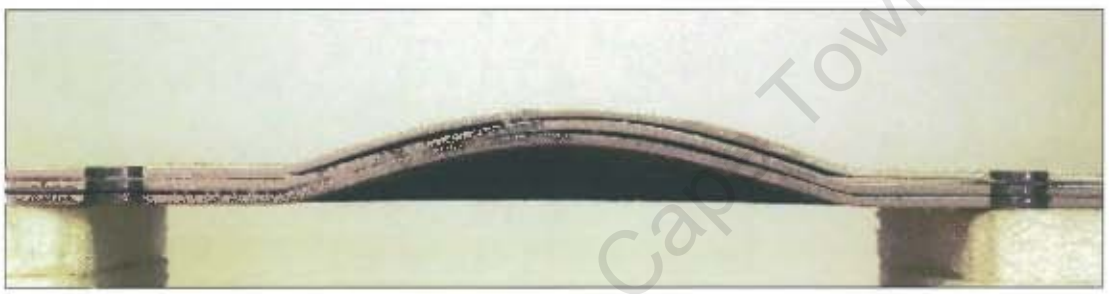


Figure 4.11: Photograph of plate profile for test plate subjected to same charge mass (7g) but different load conditions (LC-1, LC-2 and LC-3) Test plate Numbers, NJ220405c, NJ220405e, NJ220405f

4.3 Burn diameter phenomenon

A circular ring referred to as the "burn diameter" is observed on the loaded side of the test specimens. This has been observed by Nurick et al [6 - 8]. The burn diameter is observed for stand-off distances ranging from 13mm up to 75mm (Figure 4.12). In experiments with stand-off distances ranging from 100mm to 300mm an even coating of soot is observed as shown in Figure 4.13.

Burn diameter is visible after cleaning the soot from the test specimens with turpentine as shown in Figure 4.14. In cases where a uniform coating of soot was observed no visible burn diameter was observed.

Figure 4.12: Photograph of burn diameter for test specimen NJ180405a, S = 13mm, charge mass 5g, I = 10.99Ns, Load condition LC-1

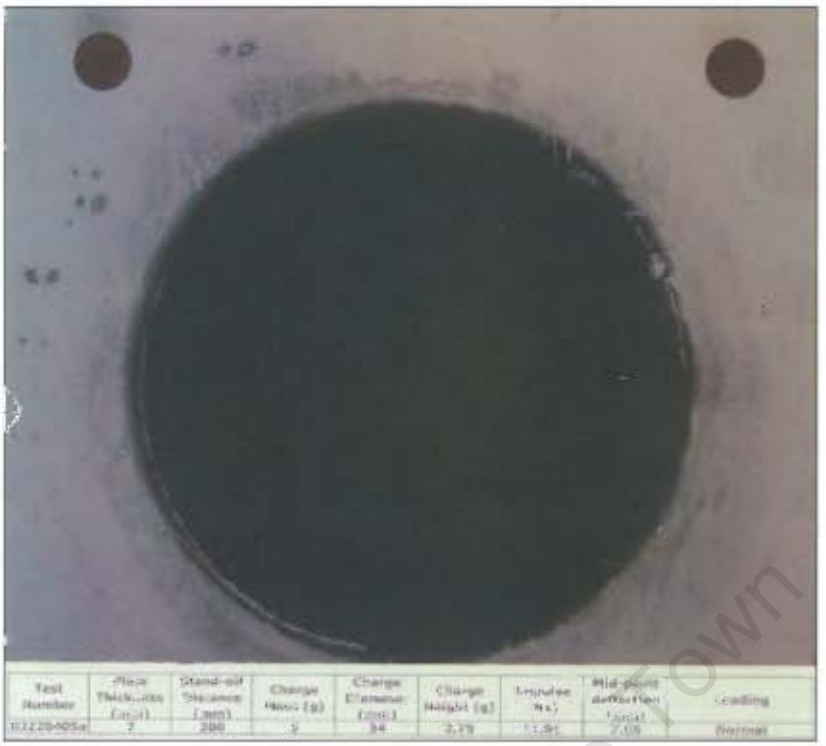


Figure 4.13: Photograph of uniform coat of soot, no visible indication of burn diameter for test specimen NJ220405a,S = 200mm, charge mass 5g, I = 11.91Ns, Load condition LC-1

Figure 4.14: Photograph of burn diameter for test specimen NJ150405c, S = 40mm, charge mass 9g, I = 17.97Ns, Load condition LC-1

4.4 Thinning

Thinning is observed in both the central area and at the boundary of the test specimens.

4.4.1 Thinning in the central region

Thinning in the central area, as shown in Figure 4.15, is a function of the distance between the test specimen and the plastic explosive. It is observed at higher impulses for stand-off distances ranging from 13mm to 40mm. An inner dome atop a larger global dome is observed within this range. Thinning coincides with the inflection diameter which demarcates the boundary between the larger global dome and the inner dome characterised by the sharp increase in gradient of the plate profile. This is similar to plate behaviour observed in localised blast loading tests, Nurick et al [6 - 8].

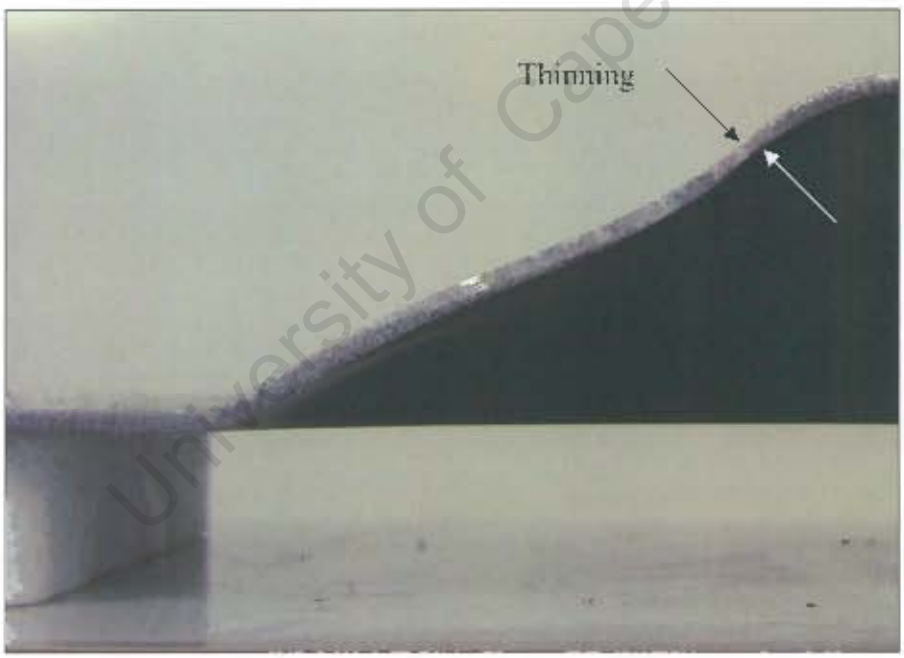


Figure 4.15: Photograph of thinning at the central area of the plate for test specimen NJ250405c, charge mass 6g, I =12.44Ns, S = 13mm

4.4.2 Thinning at the boundary

Thinning at the boundary is observed at stand-off distances ranging from 25mm to 300mm using the tubes provided the impulse was sufficiently high. Mode Ib, (necking around the entire boundary of the plate) was most prevalent. The thinning mechanism observed can be described as a sharp indentation due to the sharp edge of the clamping plate with stretching and thinning occurring thereafter [3] as shown in Figure 4.16.

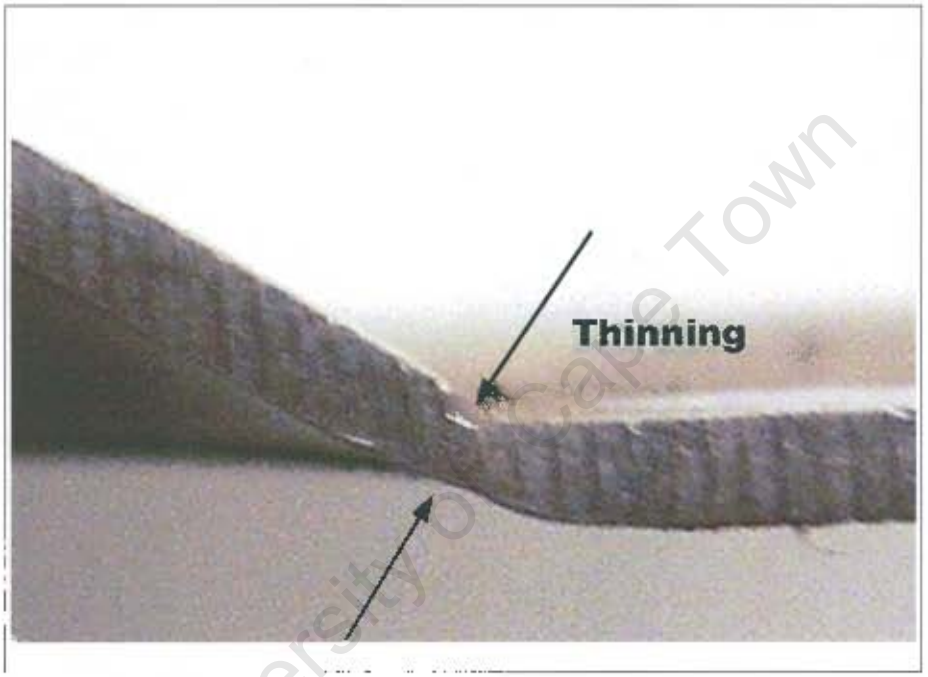


Figure 4.16: Photograph of thinning at the boundary for test specimen NJ290305g, charge mass = 15.5g, I =33.47Ns, S = 250mm

4.4.3 Tearing at the boundary

The central deformation of the test specimen increases with increasing impulse. Tearing occurs once a certain threshold impulse has been achieved. However this impulse is dependent on plate thickness. Partial tearing (Mode II*) along the boundary, as shown in Figure 4.17, was observed at stand off distances of 250mm and 150mm at impulse values of 32.1Ns and 32.44Ns respectively. However, at stand-off distance of 25mm the test plate exhibited partial tearing at the boundary and thinning in the central area of the plate at an impulse of 17.2Ns as shown in Figure 4.18. Complete tearing at the boundary was observed only in two cases at stand-off distances of 50mm and 250mm at impulses of 21.17Ns and 29.92Ns respectively, as shown in Figure 4.19. Thus, the results indicate that tearing occurs at lower impulses for smaller stand-off distances due to the severity of the blast load as the charge is moved closer to the plate.

It should be noted that the purpose of this investigation is to establish the relationship between stand-off distance and large inelastic deformation (Mode I). However, partial tearing (Mode II*) and complete tearing (Mode II) occurred during tests done to establish the limits of charge masses that could be used.

Figure 4.17: Photograph of partial tearing at the boundary of test specimen NJ060405f, charge mass 15g, I = 32.44Ns, S = 150mm

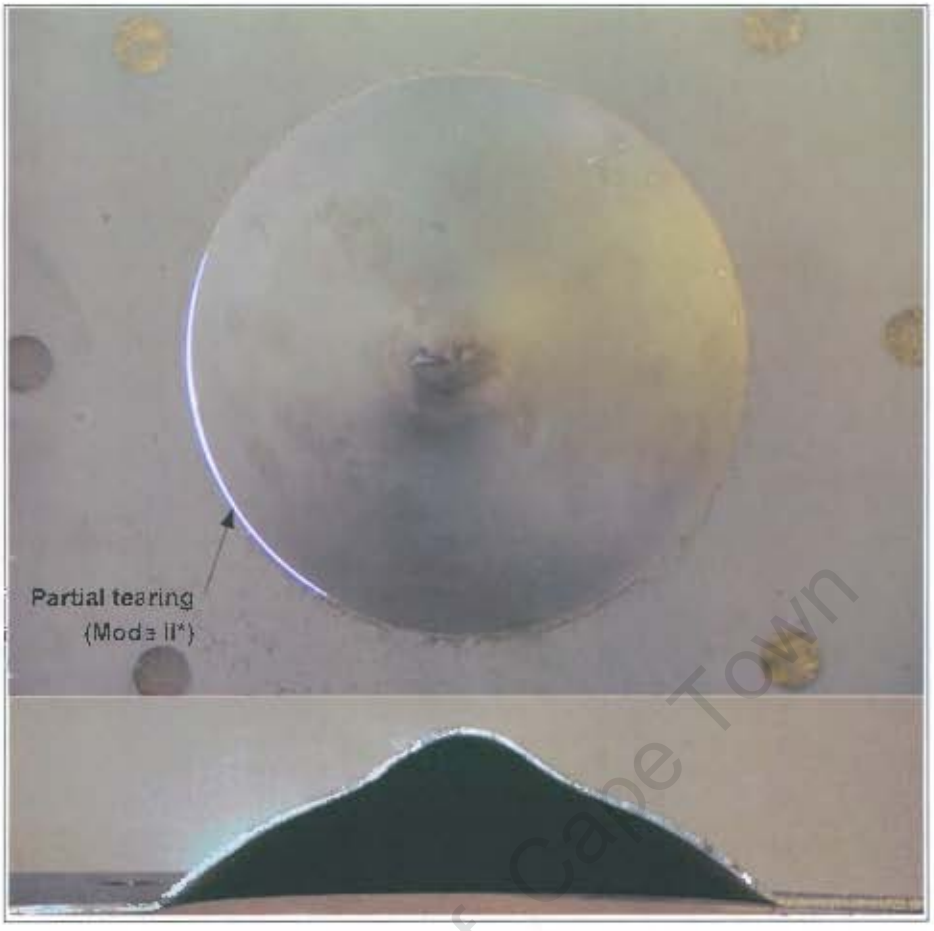


Figure 4.18: Photograph of partial tearing at the boundary with thinning at the central area of the plate of test specimen NJ160405i, charge mass 9g, I = 17.2Ns, S = 25mm

Figure 4.19: Photograph of complete tensile tearing at the boundary of test specimen NJ090405d, charge mass 11g, I = 21.17Ns, S = 50mm

4.5 Experimental results

The experimental data are presented in Table 4.1. The test plates are labelled according to the date of the test and the order in which the test were conducted. For example NJ – denotes author's initials, 250405 – date (25th April 2005), a – 1st test of the day.

The charge mass listed include the 1g leader charge attached to detonator, for example 5g equals to (4+1)g. The reader is referred to Figure 4.4 for description of the different loading conditions used.

Table 4.1: Experimental results

Test Number	Plate Thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (mm)	Impulse (Ns)	Mid-point deflection (mm)	Mid-point deflection - Plate thickness Ratio	Burn Diameter(mm)	Mode of Failure	Loading condition
NJ180405a	1.9	13	5	34	2.75	10.99	22.21	11.69	47.52	Mode I	LC-1
NJ250405a	1.9	13	4	34	2.07	8.65	18.35	9.66	45.81	Mode I	LC-4
NJ250405b	1.9	13	5	34	2.75	10.99	22.54	11.86	48.26	Mode I	LC-4
NJ250405c	1.9	13	6	34	3.44	12.44	26.45	13.92	49.61	Mode Itc	LC-4
NJ160405f	1.9	25	4	34	2.07	8.68	14.78	7.78	50.38	Mode I	LC-1
NJ160405g	1.9	25	5	34	2.75	10.33	17.34	9.12	55.08	Mode I	LC-1
NJ160405h	1.9	25	7	34	4.13	14.02	21.67	11.40	61.96	Mode Ib	LC-1
NJ160405l	1.9	25	9	34	5.51	17.20	28.10	14.79	62.06	Mode II*+Mode Itc	LC-1
NJ160405a	1.9	30	5	34	2.75	10.51	15.57	8.19	60.05	Mode I	LC-1
NJ160405b	1.9	30	7	34	4.13	14.32	22.77	11.98	63.63	Mode Ib	LC-1
NJ160405c	1.9	30	8	34	4.82	15.90	24.23	12.75	62.48	Mode Ib	LC-1
NJ160405d	1.9	30	9	34	5.51	17.16	23.80	12.53	67.10	Mode Ib	LC-1
NJ160405e	1.9	30	4	34	2.07	8.43	12.64	6.65	55.32	Mode I	LC-1
NJ150405a	1.9	40	5	34	2.75	11.40	12.34	6.50	68.35	Mode I	LC-1
NJ150405b	1.9	40	7	34	4.13	14.37	19.00	10.00	66.57	Mode Ib	LC-1
NJ150405c	1.9	40	9	34	5.51	17.97	22.26	11.71	73.38	Mode Ib	LC-1
NJ150405d	1.9	40	8	34	4.82	16.21	19.61	10.32	64.44	Mode Ib	LC-1
NJ150405e	1.9	40	4	34	2.07	8.51	10.71	5.63	61.59	Mode I	LC-1
NJ300405a	1.9	50	4	34	2.07	9.11	8.39	4.41	62.74	Mode I	LC-1
NJ090405a	1.9	50	5	34	2.75	10.59	9.84	5.18	68.44	Mode I	LC-1
NJ090405b	1.9	50	7	34	4.13	14.11	13.26	6.98	74.62	Mode Ib	LC-1
NJ090405c	1.9	50	9	34	5.51	17.94	18.12	9.54	77.36	Mode Ib	LC-1
NJ090405d	1.9	50	11	34	6.88	21.17	21.58	11.36	-	Mode II	LC-1

Test Number	Plate Thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (mm)	Impulse (Ns)	Mid-point deflection (mm)	Mid-point deflection - Plate thickness Ratio	Burn Diameter(mm)	Mode of Failure	Loading condition
NJ020705a	1.9	75	4	34	2.07	9.10	6.65	3.50	-	Mode I	LC-1
NJ020705b	1.9	75	5	34	2.75	11.33	8.28	4.36	-	Mode I	LC-1
NJ020705b	1.9	75	7	34	4.13	14.64	11.64	6.12	-	Mode I	LC-1
NJ040705a	1.9	75	9	34	5.51	17.68	13.85	7.29	-	Mode I	LC-1
NJ040705b	1.9	75	11	34	6.88	19.91	16.60	8.73	-	Mode Ib	LC-1
NJ300405b	1.9	100	4	34	2.07	9.57	5.92	3.12	-	Mode I	LC-1
NJ080405a	1.9	100	5	34	2.75	10.79	8.05	4.24	-	Mode I	LC-1
NJ080405b	1.9	100	7	34	4.13	14.76	11.66	6.13	-	Mode I	LC-1
NJ080405c	1.9	100	9	34	5.51	17.97	14.48	7.62	-	Mode I	LC-1
NJ080405d	1.9	100	11	34	6.88	21.86	17.03	8.96	-	Mode I	LC-1
NJ080405e	1.9	100	13	34	8.26	25.36	19.79	10.42	-	Mode Ib	LC-1
NJ060405a	1.9	150	5	34	2.75	11.83	8.31	4.37	-	Mode I	LC-1
NJ060405b	1.9	150	7	34	4.13	16.15	11.61	6.11	-	Mode I	LC-1
NJ060405c	1.9	150	9	34	5.51	19.00	14.37	7.56	-	Mode I	LC-1
NJ060405d	1.9	150	11	34	6.88	25.19	17.18	9.04	-	Mode I	LC-1
NJ060405e	1.9	150	13	34	8.26	28.73	20.05	10.55	-	Mode Ib	LC-1
NJ060405f	1.9	150	15	34	9.64	32.44	-	-	-	Mode II*	LC-1
NJ230405a	1.9	150	5	34	2.75	11.47	7.83	4.12	-	Mode I	LC-1
NJ230405b	1.9	150	5	34	2.75	12.03	8.50	4.47	-	Mode I	LC-2
NJ230405c	1.9	150	5	34	2.75	10.56	7.87	4.14	-	Mode I	LC-3
NJ230405d	1.9	150	7	34	4.13	15.30	11.76	6.19	-	Mode I	LC-1
NJ230405e	1.9	150	7	34	4.13	15.11	12.18	6.41	-	Mode I	LC-2
NJ230405f	1.9	150	7	34	4.13	15.30	12.28	6.46	-	Mode I	LC-3

Test Number	Plate Thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (mm)	Impulse (Ns)	Mid-point deflection (mm)	Mid-point deflection - Plate thickness Ratio	Burn Diameter(mm)	Mode of Failure	Loading condition
NJ300405c	1.9	200	4	34	2.07	9.64	5.96	3.14	-	Mode I	LC-1
NJ050405a	1.9	200	5	34	2.75	13.06	7.96	4.20	-	Mode I	LC-1
NJ050405b	1.9	200	7	34	4.13	17.35	11.29	5.94	-	Mode I	LC-1
NJ050405c	1.9	200	9	34	5.51	22.41	13.55	7.13	-	Mode I	LC-1
NJ050405d	1.9	200	11	34	6.88	25.18	16.05	8.44	-	Mode IIb	LC-1
NJ050405e	1.9	200	13	34	8.26	30.69	18.55	9.76	-	Mode IIb	LC-1
NJ050405f	1.9	200	15	34	9.64	31.67	20.01	10.53	-	Mode IIb	LC-1
NJ220405a	1.9	200	5	34	2.75	11.91	7.65	4.03	-	Mode I	LC-1
NJ220405b	1.9	200	5	34	2.75	11.67	7.82	4.12	-	Mode I	LC-2
NJ220405c	1.9	200	7	34	4.13	16.18	10.72	5.64	-	Mode I	LC-1
NJ220405d	1.9	200	5	34	2.75	11.38	8.07	4.25	-	Mode I	LC-3
NJ220405e	1.9	200	7	34	4.13	15.66	11.38	5.99	-	Mode I	LC-2
NJ220405f	1.9	200	7	34	4.13	15.26	11.14	5.86	-	Mode I	LC-3
NJ220405g	1.9	200	7	34	4.13	14.85	11.77	6.20	-	Mode I	LC-3
NJ290305a	1.9	250	11	34	6.88	24.05	15.30	8.05	-	Mode IIb	LC-1
NJ290305b	1.9	250	13	34	8.26	26.33	17.03	8.96	-	Mode IIb	LC-1
NJ290305c	1.9	250	15	34	9.64	30.24	18.92	9.96	-	Mode IIb	LC-1
NJ290305d	1.9	250	17	34	11.01	29.92	-	-	-	Mode II	LC-1
NJ290305e	1.9	250	16	34	10.33	32.10	-	-	-	Mode II*	LC-1
NJ290305f	1.9	250	5	34	2.75	11.85	7.37	3.88	-	Mode I	LC-1
NJ290305g	1.9	250	15.5	34	9.98	33.47	19.53	10.28	-	Mode IIb	LC-1

Test Number	Plate Thickness (mm)	Stand-off Distance (mm)	Charge Mass (g)	Charge Diameter (mm)	Charge Height (mm)	Impulse (Ns)	Mid-point deflection (mm)	Mid-point deflection - Plate thickness Ratio	Burn Diameter(mm)	Mode of Failure	Loading condition
NJ310305a	1.9	300	5	34	2.75	14.95	7.32	3.85	-	Mode I	LC-1
NJ310305b	1.9	300	11	34	6.88	24.82	14.97	7.88	-	Mode I	LC-1
NJ310305c	1.9	300	9	34	5.51	21.63	13.06	6.87	-	Mode I	LC-1
NJ310305d	1.9	300	13	34	8.26	30.24	18.17	9.56	-	Mode Ib	LC-1
NJ310305e	1.9	300	15	34	9.64	33.03	18.98	9.99	-	Mode Ib	LC-1
NJ210405a	1.9	300	5	34	2.75	13.32	7.01	3.69	-	Mode I	LC-1
NJ210405b	1.9	300	5	34	2.75	13.20	7.38	3.88	-	Mode I	LC-2
NJ210405c	1.9	300	5	34	2.75	12.24	7.87	4.14	-	Mode I	LC-3
NJ210405d	1.9	300	7	34	4.13	16.74	10.43	5.49	-	Mode I	LC-1
NJ210405e	1.9	300	7	34	4.13	16.30	10.27	5.41	-	Mode I	LC-2
NJ210405f	1.9	300	7	34	4.13	15.65	10.41	5.48	-	Mode I	LC-3
NJ300405d	1.9	300	4	34	2.07	10.96	5.66	2.98	-	Mode I	LC-1

5 Analysis of experimental results

This chapter examines the relationship between experimental input parameters such as mass of explosive, stand off distances and loading conditions to measured results, namely impulse and plate mid-point deflection.

5.1 Relationship between impulse and charge mass

The impulse increases for increasing charge mass and is independent of plate response. A similar trend has been reported by Nurick et al [8]. The impulses for all charge masses used in experiments are shown in Figure 5.1. A descriptive statistical analysis of the data shown in Figure 5.1 is conducted using Microsoft office EXCEL Data Analysis tool to determine the confidence interval of the best fit curve through the data points. The analysis indicates that impulse for a given charge mass will be within ±1.31Ns with a 90% confidence. Similarly, impulse will be with ±2.69Ns of the same best fit curve with a 99.9% confidence.

The regularity of the explosive can be illustrated by plotting mass of explosive to impulse ratio versus charge height. The data fall within a range of 0.4 and 0.6 as shown in Figure 5.2 in agreement with results reported by Nurick et al [6, 8].

A closer scrutiny of Figure 5.1 indicates a relationship between impulse and stand-off distance. The graph of impulse versus charge mass showing data points for stand-off distance ranging from 13mm to 50mm grouped together and subsequent stand-off distances ranging from 75mm to 300mm plotted individually is shown in Figure 5.3. It is evident that impulses measured at stand-off distance ranging from 13mm to 50mm, for a given charge mass, are less than the impulses measured (for the same charge mass) at a stand-off distance of 300mm. The relationship between impulse and stand-off distance is discussed in detail in the following Section 5.2.

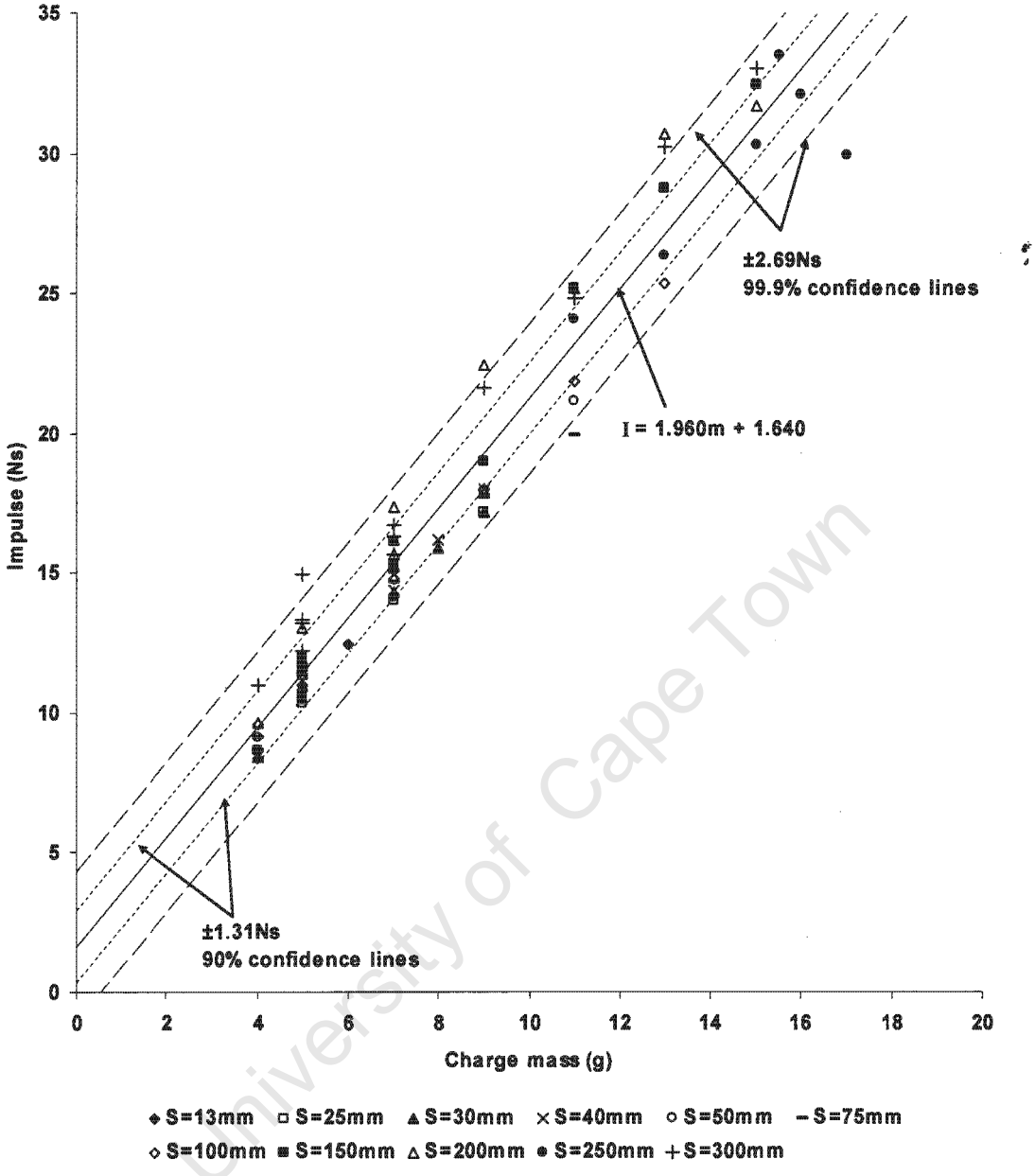


Figure 5.1: Graph of impulse versus charge mass for all tests

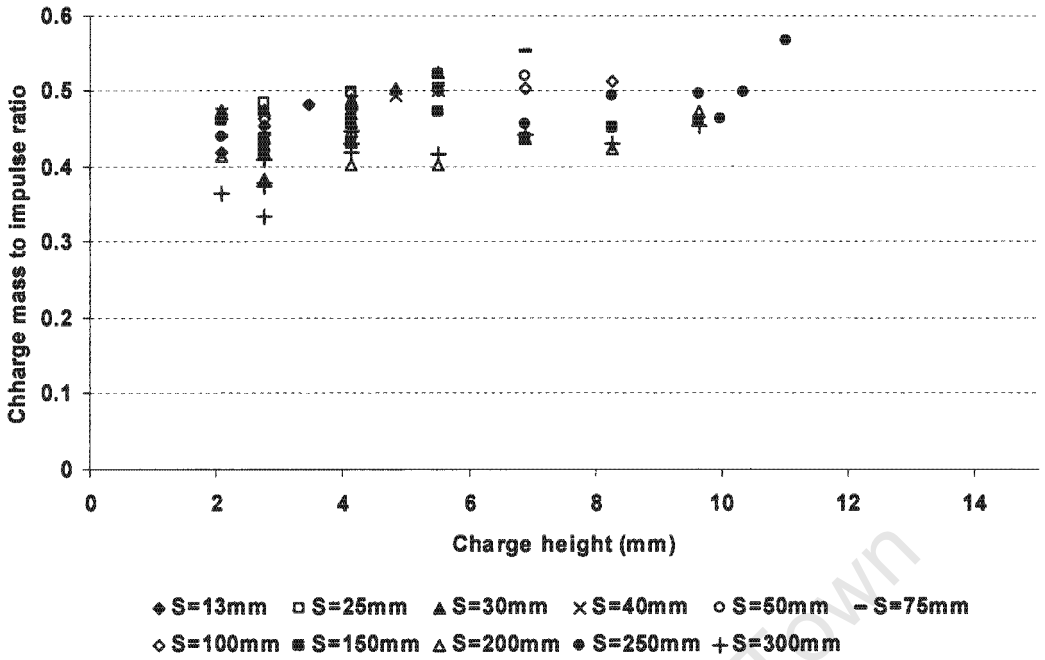


Figure 5.2: Graph of charge mass to impulse ratio versus charge height

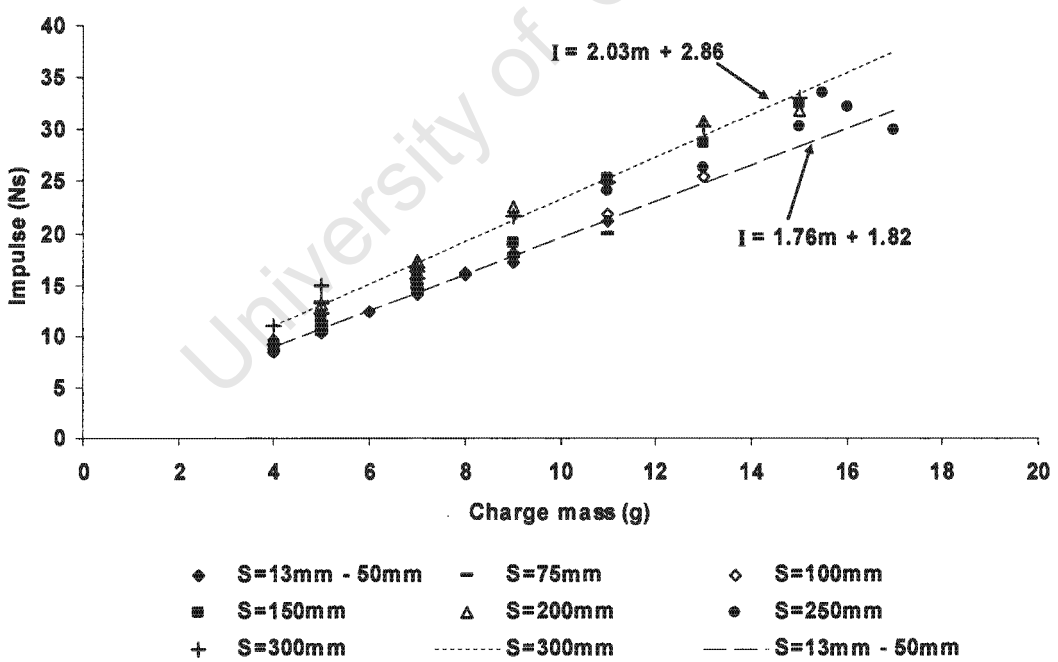


Figure 5.3: Graph of impulse versus charge mass showing the lower and upper bound in impulse due to the influence of stand-off distance

5.2 Relationship between impulse and stand-off distance

The impulses measured for a given charge mass at different stand-off distance ranging from 13mm to 300mm are shown in Figure 5.4. The data points show a gradual increase in impulse with increasing stand-off distance. The scatter in the experimental data is significantly greater for the larger charge masses 9g, 11g, 13g and 15g compared to the experimental data for charge masses 4g, 5g and 7g.

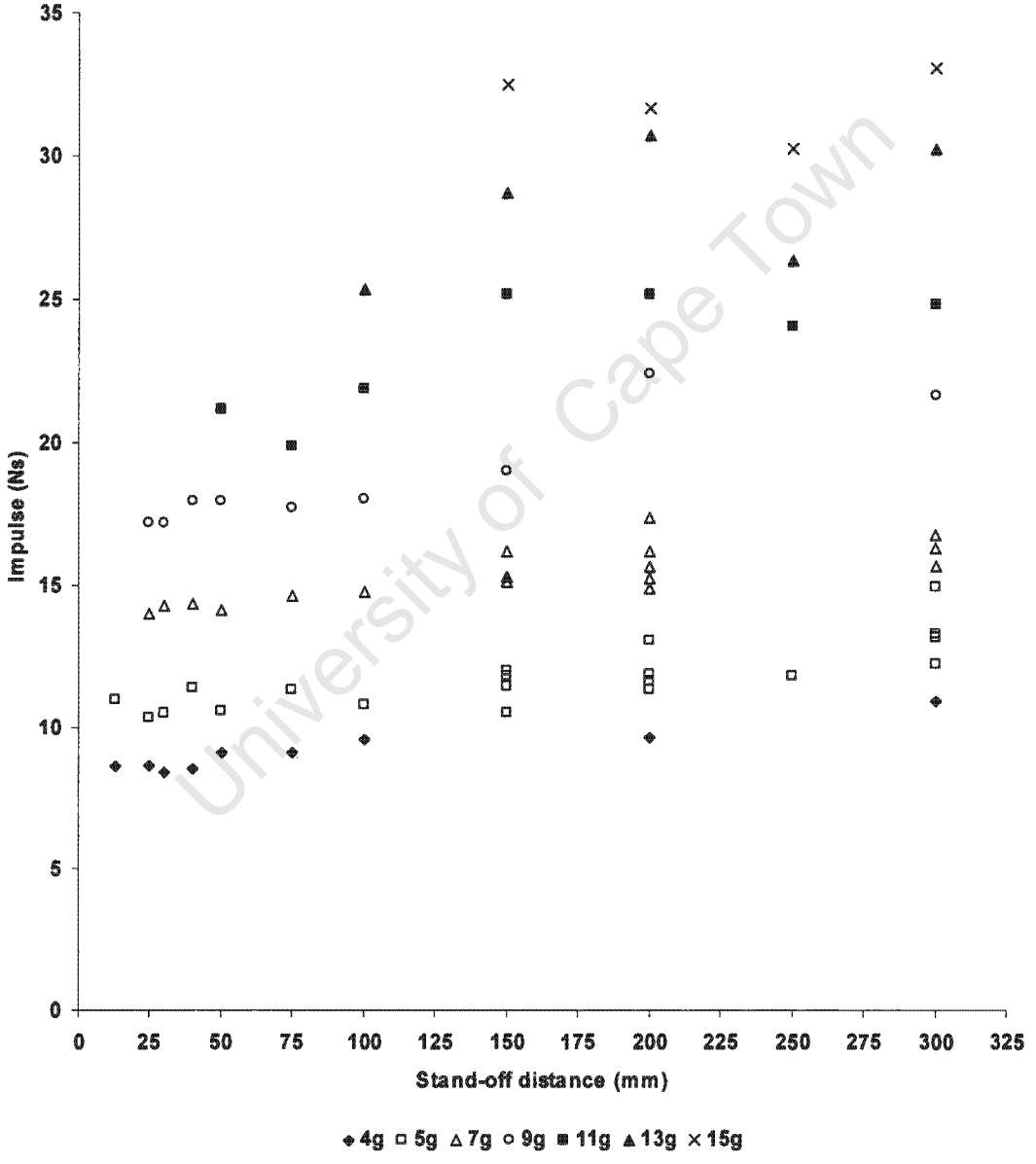


Figure 5.4: Graph of impulse versus stand-off distance for all charge masses

Best fit curves drawn through the data points for the different charge masses (4g, 5g, 7g, 9g, 11g, 13g and 15g) are shown in Figure 5.5 and Figure 5.6.

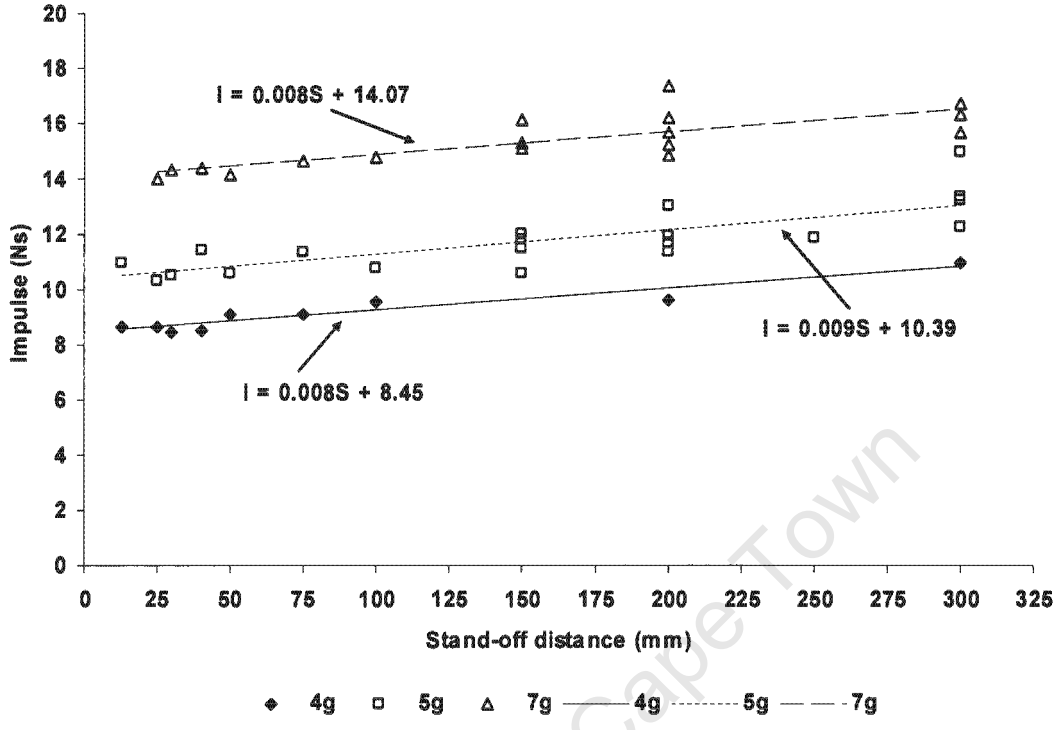


Figure 5.5: Graph of Impulse versus stand-off distance for charge masses 4g, 5g and 7g

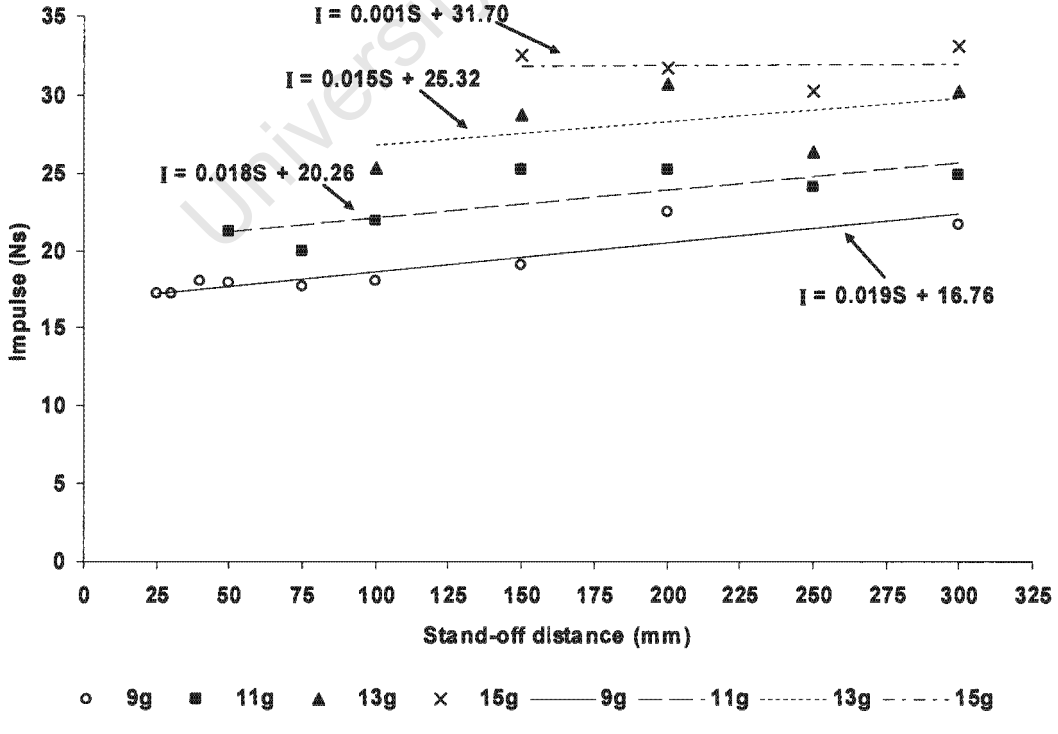


Figure 5.6: Graph of Impulse versus stand-off distance for charge masses 9g, 11g, 13g and 15g

The results show two groupings in terms of gradients of best fit curves shown in Figure 5.5 and Figure 5.6. Charge masses 4g, 5g, and 7g have comparable gradients of 0.008, 0.009 and 0.008 respectively. Whilst charge masses 9g, 11g and 13g have similar gradients of 0.019, 0.018 and 0.015. The difference in gradients of the two grouping indicates that the rate of increase in impulse with increasing stand-off distance is dependent on charge mass, with the charge masses 9g, 11g and 13g showing larger variation in impulse as compared to charge masses 4g, 5g, and 7g.

The gradual increase in impulse with increasing stand-off distance is illustrated by considering the equation of the best fit curve through the data points for charge mass 5g.

$$I = 0.009S + 10.39 \qquad \text{(eq. 5.1)}$$

The impulse calculated using equation (5.1) at stand-off distance of 13mm is equal to 10.51Ns (10.99Ns) (measured values in brackets). Similarly, at stand-off distance of 75mm, the impulse is equal to 11.06Ns (11.33Ns). The difference between the two calculated impulse values is a 5% increase at a stand-off distance of 75mm. In the case of stand-off distance 300mm, the impulse calculated using equation (5.1) is 13.09Ns (13.32Ns). The percentage increase in impulse from stand-off distance of 13mm to 300mm is equal to 20%.

The gradual increase in impulse for a given charge mass, as stand-off distance increases, is further illustrated by using the equations of the best fit curves shown in Figure 5.5 and Figure 5.6 to estimate the values of impulse (for charge masses 4g, 5g, 7g, 9g, 11g and 13g) at zero stand-off distance. This is done so as to establish a lower bound in impulse for any given charge mass with respect to stand-off distance. The calculated impulse values are plotted in the graph of impulse versus charge mass as shown in Figure 5.7. The results show an increase in impulse as stand-off distance increases for a given charge mass. The best fit curve through the data points for zero stand-off distance forms a lower bound, while the best fit curve through the data points for stand-off distance 300mm form an upper bound. The impulse values for stand-off distance ranging from 13mm to 250mm fall within the bounding best fit curves as shown in Figure 5.7.

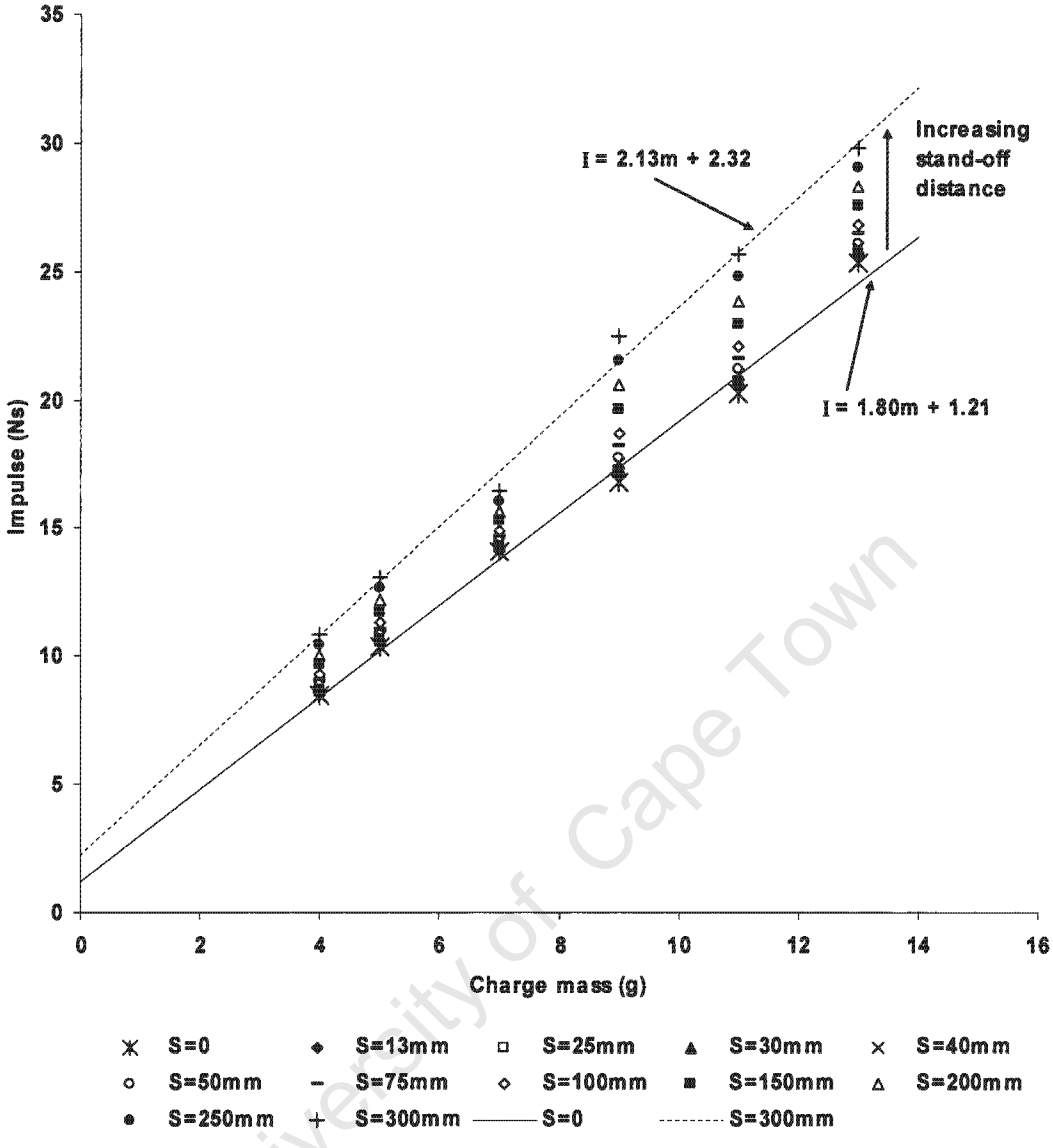


Figure 5.7: Graph of impulse versus charge mass for stand-off distances ranging from zero to 300mm calculated using the equations of the best fit curves shown in Figure 5.5 and Figure 5.6

The percentage increases in measured impulse from the closest stand-off distance to the furthest distance for different charge masses used is given in Table 5.1.

The confidence intervals of the best fit curves through the data points for charge masses 4g, 5g and 7g shown in Figure 5.5 indicate that measured impulses will be within ±0.50Ns, ±0.43Ns and ±0.38Ns respectively with 90% confidence. In the case of charge masses 9g, 11g, 13g and 15g the variation in impulse with changing stand-off distance is within ±1.19Ns, ±1.59, ±2.24 and ±1.42 of the best fit curves through the data points respectively (Figure 5.6) with a 90% confidence level.

Table 5.1: Statistical variation of impulse for different charge masses

Charge Mass (g)	Stand-off distance range	No of tests	90% confidence	Variation in impulse (Ns)		% difference
				Impulse at S=closest	Impulse at S=300mm	
4	13mm – 300mm	9	±0.50Ns	8.65	10.96	21
5	13mm – 300mm	21	±0.43Ns	10.99	14.95	27
7	25mm – 300mm	18	±0.38Ns	14.02	16.74	16
9	25mm – 300mm	9	±1.19Ns	17.20	21.63	21
11	50mm – 300mm	7	±1.59Ns	21.17	24.82	15
13	100mm – 300mm	5	±2.24Ns	25.36	30.24	16
15	150mm – 300mm	4	±1.42Ns	32.44	33.03	2

5.3 Relationship between mid-point deflection and stand-off distance

The measured mid-point deflection for a given charge mass decreases for increasing stand-off distance as shown in Figure 5.8. The trends observed from Figure 5.8 concur with information reported by Akus and Yildirim [11] for experiments on square plates subjected to blast loads at different stand-off distances and varying charge masses.

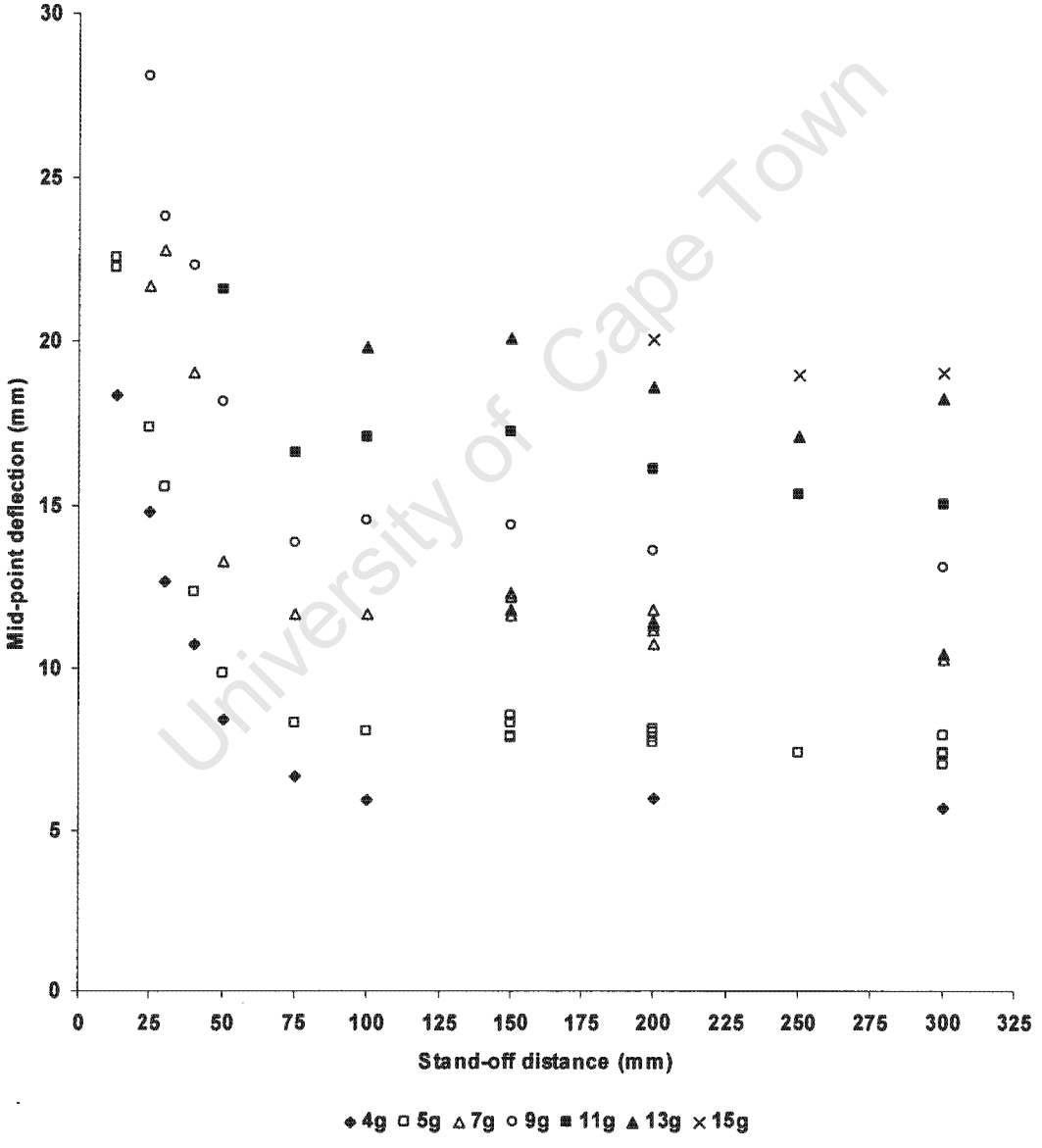


Figure 5.8: Graph of mid-point deflection versus stand-off distance

The results show a sharp decrease in mid-point deflection for stand-off distances ranging from 13mm to 50mm for a specific charge mass. The difference in mid-point deflection with respect to stand-off distance is given in Table 5.2 for charge masses 4g, 5g, 7g and 9g. The results illustrate increasing difference in mid-point deflection measured at stand-off distances of 25mm and 50mm for increasing charge mass. The percentage difference in mid-point deflection between stand-off distances 25mm and 50mm is 43%, 43%, 39% and 36% for charge masses 4g, 5g, 7g and 9g respectively. This means that mid-point deflection decreases by 57%, 57%, 61% and 64% for charge masses 4g, 5g, 7g and 9g respectively as stand-off distance is increased from 25mm to 50mm.

Alternatively, the results show that mid-point deflection increases rapidly with decreasing stand-off distance ranging from 50mm to 13mm and increasing charge mass.

Table 5.2: Variation in measured mid-point deflection for stand-off distance ranging from 25mm to 50mm for different charge masses

Charge Mass (g)	Range of stand-off distance (mm)	Range of mid-point deflection (mm)		Difference in mid-point deflection (mm)	% difference in mid-point deflection
		S=25mm	S=50mm	(S=25mm - S=50mm)	
4	25 - 50	14.78	8.39	6.39	43
5	25 - 50	17.34	9.84	7.50	43
7	25 - 50	21.67	13.26	8.41	39
9	25 - 50	28.10	18.12	9.98	36

The mid-point deflections are similar in magnitude for stand-off distances ranging from 75mm to 300mm. The maximum and minimum mid-point deflection for different charge mass for stand-off distances ranging from 75mm – 300mm is given in Table 5.3. The confidence intervals of the data points for charge masses 4g, 5g, 7g, 9g, 11g, 13g and 15g for stand-off range of 75mm to 300mm is presented in Table 5.3. The results show that there is a 90% probability that the mid-point deflection will be within approximately ±1mm of the best fit curves through the data points as shown in Figure 5.9. Nevertheless, the mid-point deflection decreases gradually with increasing stand-off distance as indicated by the gradients of the best fit curves. The decrease in mid-point deflection is least evident for charge mass 4g, as indicated by the magnitude of the gradient of the best fit curve of -0.003. Whilst, for charge mass of 15g the magnitude of the gradient of the best fit curve of -0.01, indicates that mid-

point deflection asymptotes earlier for the smaller charge masses compared to larger charge masses.

Table 5.3: Variation in measured mid-point deflection for stand-off distance ranging from 75mm to 300mm for different charge masses

Charge Mass (g)	No. data points	Range of stand-off distance (mm)	90% confidence level	Range of mid-point deflection (mm)		Difference in mid-point deflection (mm)	% difference in mid-point deflection
			(mm)	max	min	(max - min)	
4	4	75 - 300	±0.50	6.65	5.66	0.99	15
5	15	75 - 300	±0.19	8.50	7.01	1.49	18
7	14	75 - 300	±0.31	12.28	10.27	2.01	16
9	5	75 - 300	±0.56	14.48	13.06	1.42	10
11	6	75 - 300	±0.75	17.18	14.97	2.21	13
13	5	100 - 300	±1.18	20.05	17.03	3.02	15
15	3	200 - 300	±1.03	20.01	18.92	1.09	6

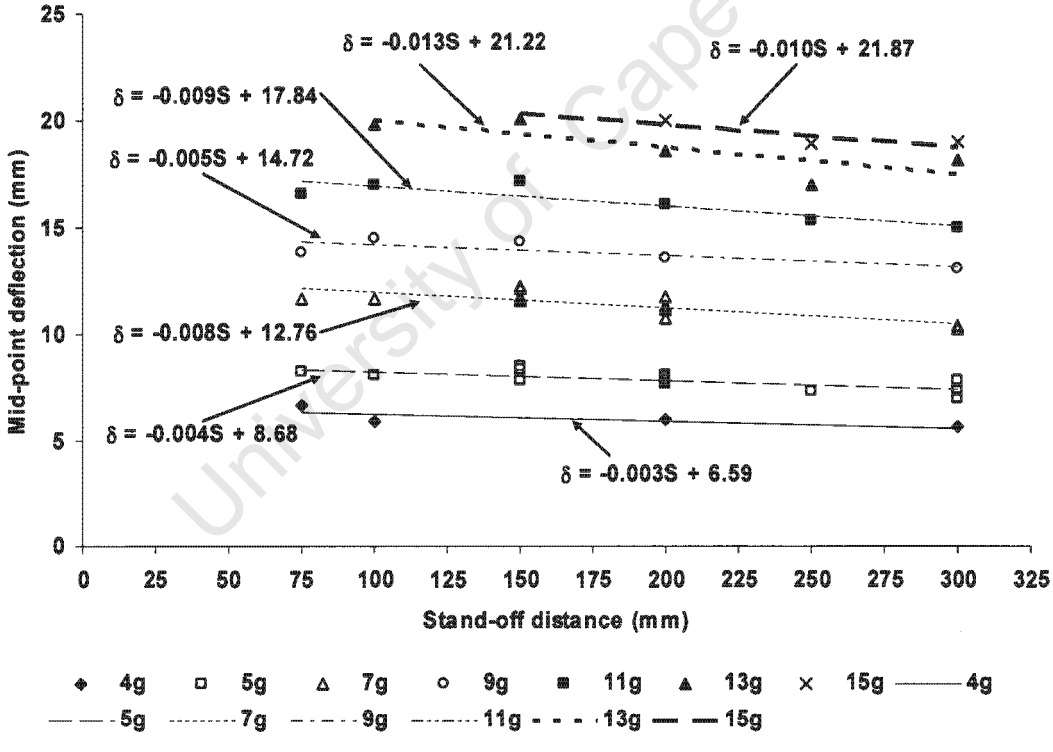


Figure 5.9: Graph of mid-point deflection versus stand-off distance, for charge masses 4g, 5g, 7g, 9g, 11g, 13g and 15g, and stand-off distance ranging from 75mm to 300mm

The experimental data shown in Figure 5.9 plotted in terms of mid-point deflection – thickness ratio and stand-off distance is shown in Figure 5.10. Analyses of the data points show that the variation of mid-point deflection – thickness ratio is within ±1 mid-point deflection – thickness ratio of the best fit curves through the data points

with 90% confidence level. The statistical variation in mid-point deflection - thickness ratio for different charge masses is given in Table 5.4 for stand-off distance ranging from 75mm to 300mm.

Table 5.4: Variation in mid-point deflection – thickness ratio for different charge masses at stand-off distances ranging from 75mm to 300mm with 90% confidence level

Charge mass (g)	Stand-off distance range (mm)	Variation in mid-point – thickness ratio
4	75 - 300	±0.26
5	75 - 300	±0.10
7	75 - 300	±0.16
9	75 - 300	±0.29
11	75 - 300	±0.39
13	75 - 300	±0.62
15	75 - 300	±0.54

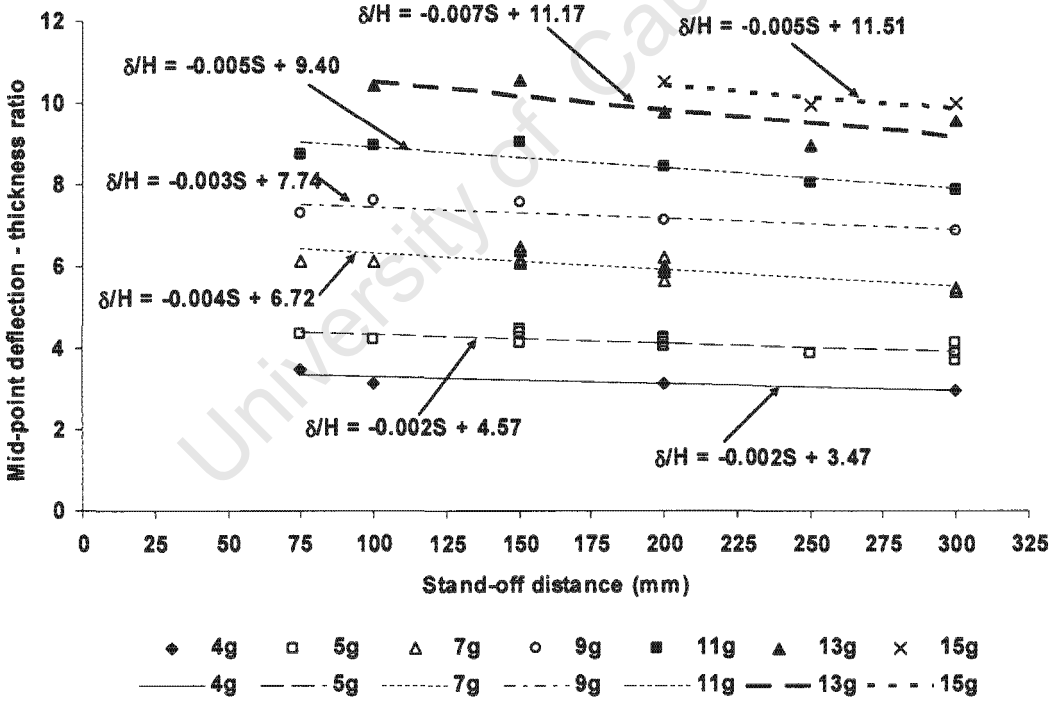


Figure 5.10: Graph of mid-point deflection – thickness ratio versus stand-off distance, for charge masses 4g, 5g, 7g, 9g, 11g, 13g and 15g, and stand-off distance ranging from 75mm to 300mm

5.4 Relationship between stand-off distance and loading condition

The distinction between the two loading conditions (namely, localised and uniform) is in accordance with the guide reported by Marchand and Alfawakhiri [33]. They propose that the loading can be assumed to be uniformly distributed over the structure if the stand-off distance is greater than one-half of the largest dimension of the structure. In the experiments described herein the plate diameter is the largest dimension. Hence uniform loading conditions should occur for stand-off distances greater than the half plate diameter (53mm). This is confirmed by the observation of large global dome for stand-off distance ranging from 100mm to 300mm as shown in Figure 5.11 to Figure 5.13. This form of deformation has been reported by Nurick et al [3, 5, 9] for uniformly loaded plates using concentric rings of explosive.

In the case of closer stand-off distances ranging from 13mm to 40mm the plate profiles show an inner dome atop a larger global dome as shown in Figure 5.11 to Figure 5.13. This concurs with similar observations reported by Nurick et al [6 - 8] for circular and quadrangular plates subjected to localised blast loads. The other notable feature observed that is unique to localised loading is burn diameter. This feature has been reported for localised loading of circular and quadrangular plates by Nurick et al [6 - 8]. This phenomenon has not been reported for uniform loading.

At stand-off distances of 50mm and 75mm the plate profile exhibits a transition phase between uniform and localised loading. The plate response at these stand-off distances exhibit aspects of localised and uniform loading. The plate profiles show a large global dome similar to that observed for stand-off distance ranging from 100mm to 300mm. However, the top of the dome is "flatter" than that observed at the larger stand-off distances as shown in Figure 5.11 and Figure 5.12 for charge masses 5g and 7g respectively. The profiles also show increased deformation on the plate closer towards the boundary similar to that observed at the stand-off distances ranging from 13mm to 40mm. Burn diameters are also observed on the loaded side of the plate for stand-off distance 50mm and 75mm

It should be noted that for charge mass 9g the plate profile at stand-off distance of 50mm show the emergence of an inner dome as shown in Figure 5.13 along with increased deformation closer to the boundary. At stand-off distance of 75mm the plate profile exhibits a "flatter" global dome with increased deformation closer to the boundary similar to that observed for charge masses 5g and 7g.

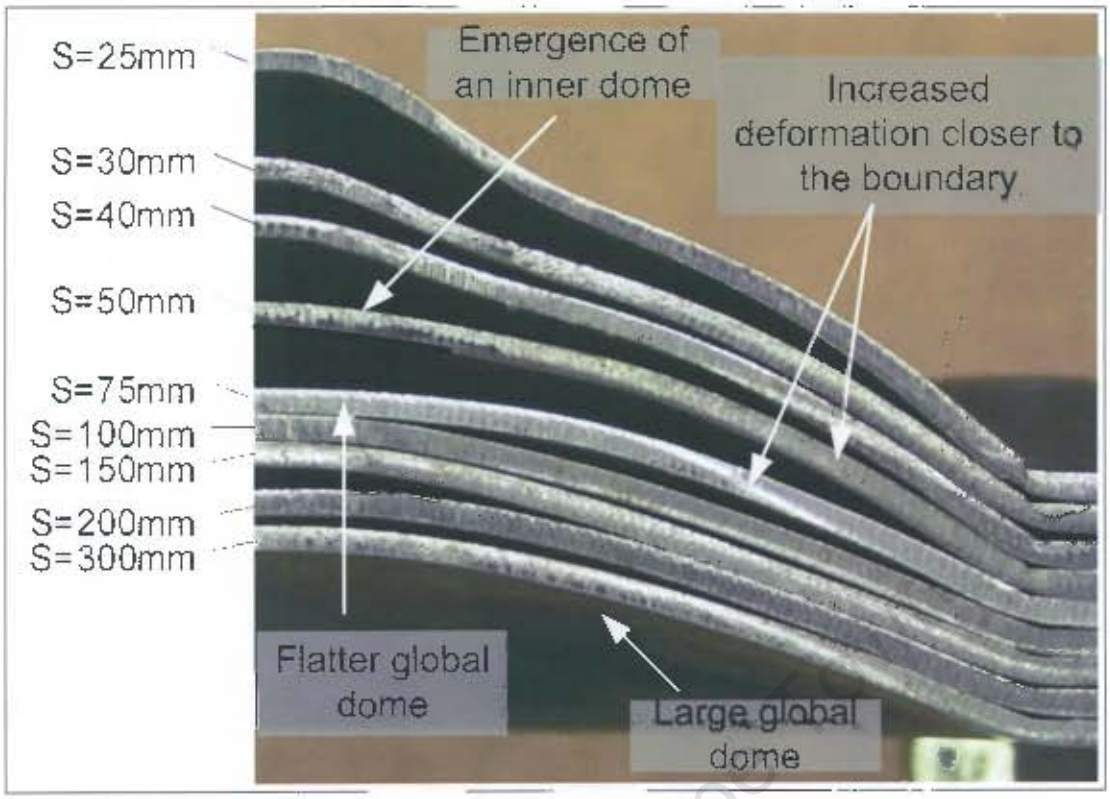


Figure 5.13: Photograph of plate profiles at different stand-off distances for charge mass 9g

The above mentioned observations indicate that classification of localised and uniform loading conditions is a function of stand-off distance and charge mass. In other words, the emergence of a "flatter" global dome in conjunction with increased deformation closer to the boundary as well as the appearance of the burn diameter mark the transition to localised loading as the charge is moved nearer to the plate for a given charge mass.

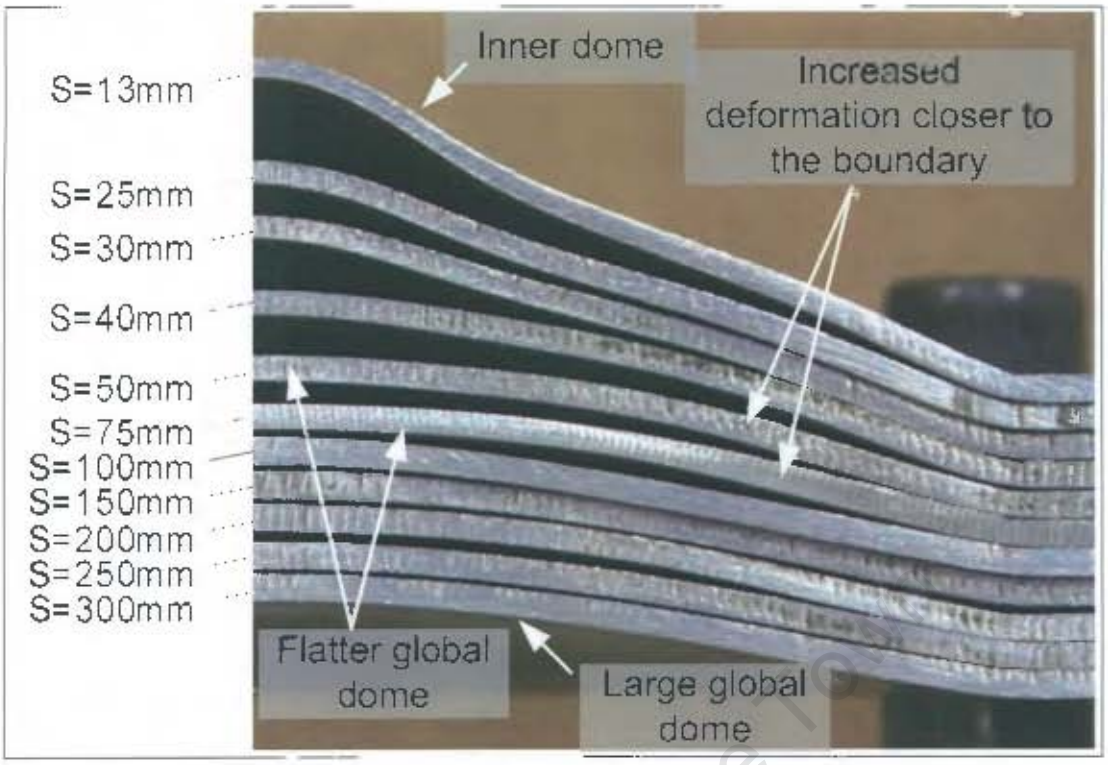


Figure 5.11: Photograph of plate profiles at different stand-off distances for charge mass 5g

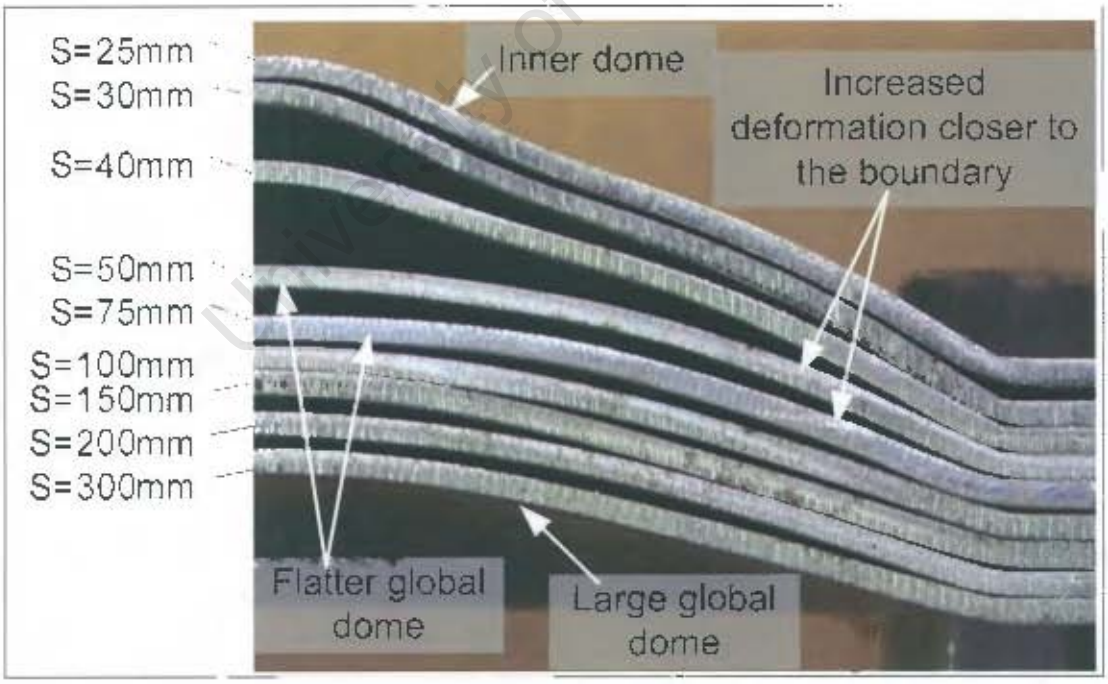


Figure 5.12: Photograph of plate profiles at different stand-off distances for charge mass 7g