CHAPTER 5

RESULTS

5.1 Phase 1 Effect of irradiation on physico-chemical properties of maize flour, bean flour and their 70/30 composite flours

During Phase 1, various effects of irradiation on maize and bean flours were investigated. Firstly, the effects of irradiation on chemical composition of maize and bean flours were investigated. Secondly, the effects of irradiation on the viscosity of porridge made from maize flour, bean flour and their 70/30 maize:bean composite flours were determined. Thirdly, the effects of irradiation on *in vitro* starch digestibility of maize and bean flours were investigated. Fourthly, the effects of irradiation on *in vitro* protein digestibility of maize and bean flours were investigated. Fifthly, the effects of irradiation on the size and shape starch in whole maize and bean flours were investigated by scanning electron microscope.

5.1.1 *Effect of irradiation on the proximate chemical composition of maize and bean flours*

Irradiation had no significant (p>0.05) effect on the proximate chemical composition of maize flours (Table 4). Irradiation had no significant (p>0.05) on the proximate chemical composition of bean flours (Table 5).

5.1.2 *Effect of irradiation on the viscosity of porridge made from maize flour, bean flour and 70/30 maize:bean composite flour*

The pasting properties of porridges made from irradiated maize flour, bean flour and their 70/30 maize:bean composite flours were determined at 15, 20 and 25% total solids content for flours treated at 0, 2.5, 5, 7.5 and 10 kGy. The results are shown in Figures 9 to 11 and Tables 6 to 11.

Table 4 Effect of irradiation on the proximate chemical composition of maize flour

	Irradiation dose (kGy)[1]		
	0	**5**	**10**
Moisture (% wet basis)	14.1±0.16a[2]	13.8±0.31a	13.9±0.22 a
Protein (% dry basis)	9.2±0.31a	9.3±0.42a	9.2±0.17a
Crude fat (% dry basis)	0.9±0.22a	0.8±0.16a	0.9±0.14a
Ash (% dry basis)	1.4±0.12a	1.4±0.25a	1.3±0.62a
Starch (% dry basis)	70.5±0.83a	70.3±0.95a	70.4±1.2a

[1] Values are means of three replicates determined six times ±standard deviation
[2] Mean values in a row with the same letters did not differ significantly at p>0.05

Table 5 Effect of irradiation on the proximate chemical composition of bean flour

	Irradiation dose (kGy)[1]		
	0	**5**	**10**
Moisture (% wet basis)	9.8±0.25a[2]	9.7±0.33a	9.8±0.16a
Protein (% dry basis)	24.8±0.42a	24.9±0.18a	24.8±0.41a
Crude fat (% dry basis)	0.9±0.21a	0.9±0.18a	0.8±0.33a
Ash (% dry basis)	2.7±0.31a	2.8±0.24a	2.7±0.28a
Starch (% dry basis)	54.2±0.30a	54.6±0.19a	55.2±0.47a

[1] Values are means of three replicates determined six times ±standard deviation
[2] Mean values with the same letter in a row did not differ significantly at p>0.05

Irradiation reduced the viscosity of porridges made from maize flour, bean flour and their 70/30 composite flour significantly ($p \leq 0.05$). Reductions in viscosity of the porridges were dose dependent (Figures 9-11, Tables 6-11).

The peak paste viscosity or the highest viscosity of the porridge during gelatinisation was reduced significantly ($p \leq 0.05$) by irradiation of maize flour, bean flour and their 70/30 composite flours (Tables 6, 7 and 8). The breakdown viscosity or the viscosity of porridges being stirred at a constant temperature was affected significantly ($p \leq 0.05$) by irradiation (Tables 6, 7 and 8). During stirring at a constant highest temperature the porridge viscosity is reduced due to breakdown of hydrogen bonds between gelatinised starch molecules by the action of the stirrer. The setback viscosity is the viscosity of porridges on cooling from the gelatinisation temperature. It takes place due to formation of hydrogen bonds between amylose molecules. Porridges made from flours with high amylose contents develop higher setback viscosities. Setback viscosities of porridges made from irradiated maize flour, bean flour and their 70/30 composite flours were also affected significantly ($p \leq 0.05$) by irradiation (Tables 9, 10 and 11).

Figure 9a (not drawn to scale) shows that viscosity of the 15% total solids content porridges made from maize flour was reduced significantly ($p \leq 0.05$). Irradiation caused a reduction in peak paste viscosity of maize porridges by 48% at 2.5 kGy, 71% at 5.0 kGy, 84% at 7.5 kGy and 88% at 10 kGy for the 15% total solids content porridges (Table 6). Irradiation also caused a reduction in breakdown viscosity of 57% at 2.5 kGy, 76% at 5 kGy, 88% at 7.5 kGy and 92% at 10 kGy for the 15% total solids content maize porridges at 540°C (Table 6). Irradiation caused reductions in viscosity of the 15% total solids content maize porridges at setback temperature of 40°C by 31% at 2.5 kGy, by 53% at 5 kGy, by 69% at 7.5 kGy and by 77% at 10 kGy compared to the untreated control (Table 9).

Figure 9b (not drawn to scale) shows that irradiation had a significant ($p \leq 0.05$) reduction effect on the viscosity of a 20% total solids content porridges made from maize flour. Irradiation caused a significant ($p \leq 0.05$) reduction in the peak paste viscosity of a 20% total solids content maize porridge. The peak paste viscosity was reduced by 45% at 2.5 kGy, by 64% at 5.0 kGy, 80% at 7.5 kGy and by 86% at 10 kGy (Table 6). The breakdown viscosity of 20% total solids content maize porridges were also reduced significantly ($p \leq 0.05$) by irradiation. The breakdown viscosity of a 20% total solids content maize porridges was reduced by 41% at 2.5 kGy, 59% at 5.0 kGy, 75% at 7.5 kGy and by 82% at 10 kGy (Table 6). The viscosity of the 20% total solids content maize porridges at setback temperature of 40 °C was reduced by 30% at 2.5 kGy, by 52% at

5 kGy, by 72% at 7.5 kGy and by 75% at 10 kGy compared to the untreated control (Figure 9b, not drawn to scale).

Table 6 Effect of irradiation of maize flour on the peak paste viscosity and breakdown viscosity of porridges at 15, 20 and 25% total solids content (w/v)

Irradiation dose	**Peak paste viscosity[1] (cP)**			**Breakdown viscosity[1] (cP)**		
(kGy)	**15%[2]**	**20%**	**25%**	**15%[2]**	**20%**	**25%**
0	2413±57e[3]	5050±24e	8300±72e	2060±54e	3610±48e	5910±42
2.5	1258±63d	2762±38d	5744±83d	887±63d	2146±41d	4769±25d
	(-48%)[4]	(-45%)	(-31%)	(-57%)	(-41%)	(-19%)
5.0	698±22c	1823±44c	3934±75c	490±36c	1476±53c	3510±27c
	(-71%)	(-64%)	(-53%)	(-76%)	(-59%)	(-41%)
7.5	396±41b	1025±28b	31741±48b	255±41b	892±55b	2329±62b
	(-84%)	(-80%)	(-62%)	(-88%)	(-75%)	(-61%)
10	292±31a	722±42a	1912±56a	171±31a	641±24a	1687±44a
	(-88%)	(-86%)	(-77%)	(-92%)	(-82%)	(-72%)

[1] Values are means of three replicates determined six times ± standard deviation
[2] Values are percentage total solids content (w/v)
[3] Values followed by different letters in the same column differ significantly at $p \leq 0.05$
[4] Values are reduction in viscosity as a percentage of the viscosity at 0 kGy

Figure 9c, (not drawn to scale), shows that irradiation reduced the viscosity of the 25% total solids content porridges made from maize flour irradiated at 0, 2.5, 5, 7.5 and 10 kGy significantly at $p \leq 0.05$. Irradiation also had significant effects on the peak paste viscosity. The peak paste viscosity of the 25% total solids content porridges were reduced by 31% at 2.5 kGy, 53% at 5.0 kGy, 62% at 7.5 kGy and by 77% at 10 kGy (Table 6). Irradiation also had significant ($p \leq 0.05$) effect on the breakdown viscosity of 25% total solids content maize porridges. Breakdown viscosity of the 25% total solids content maize porridge was reduced by 19% at 2.5 kGy, 41% at 5.0 kGy, 61% at 7.5 kGy and by 72% at 10 kGy (Table 6). At setback temperature of 30°C, irradiation caused decreases in viscosity of a 25% total solids content maize porridges by 31% at 2.5 kGy, by 54% at 5 kGy, by 69% at 7.5 kGy and by 74% at 10 kGy compared to the untreated control (Figure 9c, not drawn to scale).

Figure 10a (not drawn to scale) shows that irradiation reduced the setback viscosity of the 15% total solids content bean porridges significantly ($p \leq 0.05$) at 30°C. Irradiation reduced the peak paste viscosity of the 15% total solids content bean porridges significantly ($p \leq 0.05$). The peak paste viscosity of the 15% total solids content bean porridges were reduced by 29% at 2.5 kGy, 47% at 5.0 kGy, 64% at 7.5 kGy and by 76% at 10 kGy (Table 7). Irradiation also reduced the breakdown viscosity significantly at ($p \leq 0.05$). The breakdown viscosity of the 15% total solids content porridges were reduced by 25% at 2.5 kGy, 42% at 5.0 kGy, 62% at 7.5 kGy and by 73% at 10 kGy compared to the untreated control (Table 7). Irradiation caused decreases in setback viscosity of the 15% total solids content bean porridges by 25% at 2.5 kGy, by 47% at 5kGy, by 58% at 7.5 kGy and by 67% at 10 kGy compared to the untreated control at 30° C (Figure 10a, not drawn to scale).

Figure 10b, (not drawn to scale), shows that irradiation reduced the viscosity of the 20% total solids porridges made from irradiated bean flour significantly ($p \leq 0.05$). Irradiation had significant ($p \leq 0.05$) effects on the peak paste viscosities of porridges made from bean flour at 20% total solids content. The peak paste viscosities of a 20% total solids content bean porridges were reduced by 16% at 2.5 kGy, 32% at 5.0 kGy, 50% at 7.5 kGy and by 60% at 10 kGy (Table 7). Irradiation also had significant effect ($p \leq 0.05$) on the breakdown viscosity of 20% total solids content porridges. The breakdown viscosity of 20% total solids content porridges was reduced by 20% at 2.5 kGy, 39% at 5.0 kGy, 62% at 7.5 kGy, and by 69% at 10 kGy (Table 7). Irradiation caused decreases in the setback viscosity of the 20 % total solids content bean porridges by 24% at 2.5 kGy, by 45% at 5 kGy, by 57% at 7.5 kGy and by 67% at 10 kGy compared to the untreated control at 30°C (Figure 10b, not drawn to scale).

Irradiation resulted in significant ($p \leq 0.05$) reductions in the setback viscosity of the 25% total solids content porridges prepared from bean flour (Figure 10c, not drawn to scale).

Irradiation reduced the peak paste viscosity of the 25% total solids content bean porridges by 20% at 2.5 kGy, 43% at 5.0 kGy, 55% at 7.5 kGy and by 66% at 10 kGy (Table 7).

Table 7 Effect of irradiation of bean flour on the peak paste viscosity and breakdown viscosity of porridges at 15, 20 and 25% total solids content (w/v)

Irradiation dose (kGy)	Peak paste viscosity[1] (cP)			Breakdown viscosity[1] (cP)		
	15%[2]	**20%**	**25%**	**15%[2]**	**20%**	**25%**
0	1231±52e[3]	3209±64e	6118±96e	1121±51e	2311±58e	5106±83e
2.5	873±22d (-29%)[4]	2687±49d (-16%)	4926±73d (-20%)	836±41d (-25%)	1849±62d (-20%)	4445±88d (-12%)
5.0	653±34c (-47%)	2192±44c (-32%)	3516±77c (-43%)	644±31c (-42%)	1418±56c (-39%)	3687±49c (-28%)
7.5	445±50b (-64%)	1613±71b (-50%)	2736±22b (-55%)	428±18b (-62%)	971±27b (-58%)	2880±39b (-44%)
10	301±12a (-76%)	1286±42a (-60%)	2106±44a (-66%)	299±11a (-73%)	723±42a (-69%)	2323±28a (-54%)

[1] Values are means of three replicates determined six times ± standard deviation
[2] Values are percentage total solids content (w/v)
[3] Values followed by different letters in the same column differ significantly at $p \leq 0.05$
[4] Values are reduction in viscosity as a percentage of the viscosity at 0 kGy

The breakdown viscosity of the 25% total solids content porridges made from bean flours were also significantly reduced by irradiation. The breakdown viscosity of 25% total solids content porridges made from bean flours were reduced by 12% at 2.5 kGy, 28% at 5.0 kGy, 44% at 7.5 kGy and by 54% at 10 kGy compared to the untreated control (Table 7). Irradiation reduced the setback viscosity of the 25% total solids content bean porridges at setback temperature of 30°C by 23% at 2.5 kGy, by 44% at 5 kGy, by 56% at 7.5 kGy and by 66% at 10 kGy compared to the untreated control (Figure 10c, not drawn to scale).

Figure 11a (not drawn to scale) shows that irradiation reduced the setback viscosity of the 15% total solids content of the porridges made from 70/30 maize:bean composite flour significantly ($p \leq 0.05$).

Irradiation significantly ($p \leq 0.05$) reduced the peak paste viscosity of porridges prepared from the 70/30 maize:bean composite flours. The peak paste viscosity of the 15% total solids content porridges made from the 70/30 maize:bean composite flours were reduced by 52% at 2.5 kGy, 67% at 5.0 kGy, 80% at 7.5 kGy and by 86% at 10 kGy (Table 8). Irradiation also had a significant ($p \leq 0.05$) effect on the breakdown viscosity of 15% total solids content porridges prepared from 70/30 maize:bean composite flours (Table 8). Irradiation caused reductions in the viscosity of the 15% total solids content porridges prepared from the 70/30 maize:bean composite flour at setback temperature of 30°C by 29% at 2.5 kGy, by 51% at 5 kGy, by 66% at 7.5 kGy and by 74% at 10 kGy compared to the untreated control at setback temperature (Figure 11a, not drawn to scale).

Table 8 Effect of irradiation of 70/30 maize:bean composite flours on the peak paste viscosity and breakdown viscosity of porridges at 15, 20 and 25% total solids content (w/v)

Irradiation dose (kGy)	Peak paste viscosity[1] (cP)			Breakdown viscosity (cP)		
	15%[2]	20%	25%	15%[2]	20%	25%
0	2041±63e[3]	4495±77e	7611±82e	1772±36e[3]	3217±43e	5673±52e
2.5	972±41d (-52%)[4]	2274±53d (-49%)	5497±48d (-28%)	872±41d (-51%)	2109±55d (-34%)	4559±64 (-20%)d
5.0	684±16c (-67%)	1934±28c (-60%)	3807±55c (-50%)	536±27c (-70%)	1539±51c (-52%)	3389±28c (-40%)
7.5	406±11b (-80%)	1202±32b (-73%)	2610±28b (-66%)	308±19b (-83%)	1014±45b (-69%)	2273±26b (-60%)
10	293±10a (-86%)	891±18a (-80%)	1962±44a (-74%)	192±13a (-89%)	765±28a (-76%)	1660±31a (-71%)

[1] Values are means of three replicates determined six times ± standard deviation
[2] Values are percentage total solids content (w/v)
[3] Values followed by different letters in the same column differ significantly at $p \leq 0.05$
[4] Values are reductions in viscosity as a percentage of the viscosity at 0 kGy

Irradiation significantly (p≤0.05) reduced the peak paste viscosity of the 20% total solids content porridges prepared from 70/30 maize:bean composite flours. The peak paste viscosity of the 20 % total solids content 70/30 maize:bean composite flour porridges were reduced by 49% at 2.5 kGy, 60% at 5.0 kGy, 73% at 7.5 kGy and by 80% at 10 kGy (Table 8). Irradiation also reduced the breakdown viscosity of 20% total solids content porridges prepared from 70/30 maize:bean composite flours. The breakdown viscosities of porridges prepared from 70/30 maize:bean composite flours were reduced by 34% at 2.5 kGy, 52% at 5.0 kGy, 69% at 7.5 kGy and by 76% at 10 kGy compared to the untreated control (Table 8). Irradiation resulted in reductions in setback viscosity of the 20% total solids content porridges prepared from the 70/30 maize:bean composite flour at setback temperature of 30°C by 28% at 2.5 kGy, by 50% at 5 kGy, by 67% at 7.5 kGy and by 73% at 10 kGy compared to the untreated control (Figure 11b, not drawn to scale).

Irradiation reduced the peak paste viscosity of the 25% total solids content porridges prepared from 70/30 maize:bean composite flours by 28% at 2.5 kGy, 50% at 5.0 kGy, 66% at 7.5 kGy and by 74% at 10 kGy (Table 8). Irradiation reduced the breakdown viscosity of the 25% total solids content porridges prepared from 70/30 maize:bean composite flours by 20% at 2.5 kGy, 40% at 5.0 kGy, 60% at 7.5 kGy and by 71% at 10 kGy compared to the untreated control (Table 8). Irradiation resulted in significant (p≤0.05) reductions in setback viscosity of 25% total solids content porridges prepared from 70/30 maize:bean flour. The setback viscosity of 25% total solids content porridge made from 70/30 maize:bean flour was reduced by 29% at 2.5 kGy, by 51% at 5 kGy, by 65% at 7.5 kGy and by 71% at 10 kGy compared to the untreated control at the setback temperature of 30°C (Figure 11c, not drawn to scale).

Figures 10 and 11 and Tables 9 and 10 show that the reductions in viscosity at setback temperature of 30°C were greater in irradiated maize flour than in irradiated bean flour. However, the viscosity of the porridge made from their 70/30 composite flour was below that of the porridge made from irradiated maize flour but above that of the porridge made from irradiated bean flour (Figure 11 and Table 11).

Table 9 Effect of irradiation of maize flour on the viscosity of porridges at 15, 20 and 25% total solids contents (w/v) at setback temperatures of 50, 40 and 30°C

Total solids content (% dry basis)	Irradiation dose (kGy)	Setback viscosity (cP)[1]		
		50°C	40°C	30°C
15	0	3619±27i	4774±188f	>6000
	2.5	1648±23f	2054±49d	1763±10d
	5.0	762±22c	1038±31c	1763±10c
	7.5	351±15b	553±20b	748±6b
	10	279±16a	344±18a	447±7a
20	0	>6000[3]	>6000	>6000
	2.5	5429±28k	>6000	>6000
	5	2911±35h	4171±16e	>6000
	7.5	1285±24e	2130±24d	5391±10f
	10	952±15d	1900±56d	3546±22e
25	0	>6000	>6000	>6000
	2.5	>6000	>6000	>6000
	5	>6000	>6000	>6000
	7.5	3853±19j	>6000	>6000
	10	2367±16g	5740±36g	>6000

[1]Values are mean of three replicates determined six times ± standard deviations
[2]Mean values followed by different letters in the same column differ significantly at $p \leq 0.05$
[3]The Rapid Visco Analyser only gives true viscosity readings up to 6000 cP

With the 15% total solids content porridges, for example, the viscosity of porridges made from irradiated maize flour was reduced by 31% at 2.5 kGy, by 53% at 5 kGy, by 69% at 7.5 kGy and by 77% at 10 kGy compared to the untreated control at setback temperature of 30°C (Table 11). The setback viscosity of the 15% total solid content porridges made from irradiated bean flour was reduced by 24% at 2.5 kGy, by 47% at 5 kGy, by 58% at 7.5 kGy and by 67% at 10 kGy compared to the untreated control at 30°C.

Table 10 Effect of irradiation of bean flour on the viscosity of porridges at 15, 20 and 25% total solids contents (w/v) at setback temperatures of 50, 40 and 30°C

Total solids content (% dry basis)	Irradiation dose (kGy)	Setback viscosity (cP)[1]		
		50°C	40°C	30°C
15	0	1330±13c	1446±21e	1838±18e
	2.5	1251±25d	1427±7d	1631±19d
	5.0	850±16c	1118±11c	1514±49c
	7.5	539±12b	634±10b	837±19b
	10	459±17a	588±8a	735±13a
20	0	3748±85k	4578±19j	>6000[3]
	2.5	3248±26j	3457±29i	3931±18i
	5.0	2345±24h	2490±24h	2818±12h
	7.5	1744±23g	1787±13g	2434±17g
	10	1474±19f	1580±14f	2434±17f
25	0	>6000	>6000	>6000
	2.5	>6000	>6000	>6000
	5	>6000	>6000	>6000
	7.5	3826±231	>6000	>6000
	10	2663±22i	4578±16j	5763±26j

[1]Values are mean of three replicates determined six times ± standard deviations

[2]Mean values followed by different letters in the same column differ significantly at p≤0.05
[3]The Rapid Visco Analyser only gives true viscosity readings up to 6000 cP

The setback viscosity of the 15% total solids content porridges made from irradiated 70/30 maize:bean composite flour was reduced by 29% at 2.5 kGy, by 51% at 5 kGy, by 66% at 7.5 kGy and by 74% at 10 kGy compared to the untreated control at setback temperature of 30°C.

Table 11 Effect of irradiation of 70/30 miaize:bean composite flour on the viscosity of porridges at15, 20 and 25% total solids contents (w/v) at setback temperatures of 50, 40 and 30°C

Total solids content (% dry basis)	Irradiation dose (kGy)	Setback viscosity (cP)[1]		
		50°C	40°C	30°C
15	0	3992±67j	4330±18h	5955±40i
	2.5	2216±47f	2834±18f	3879±30f
	5.0	1327±21c	1852±36c	2451±33d
	7.5	742±16b	1156±27b	1408±16b
	10	464±17a	749±10a	903±5a
20	0	>6000[3]	>6000	>6000
	2.5	4457±16k	>6000	>6000
	5	2692±29g	3511±39g	4376±21g
	7.5	1745±12e	2495±15e	3759±21e
	10	1427±9d	1789±16d	2354±20c
25	0	>6000	>6000	>6000
	2.5	>6000	>6000	>6000
	5	>6000	>6000	>6000
	7.5	3950±20j	>6000	>6000
	10	2732±12h	5506±22i	5859±53h

[1] Values are mean of three replicates determined six times ± standard deviations
[2] Mean values followed by a different letter in the same column differ significantly at p≤0.05
[3] The Rapid Visco Analyser only gives true viscosity readings up to 6000 cP

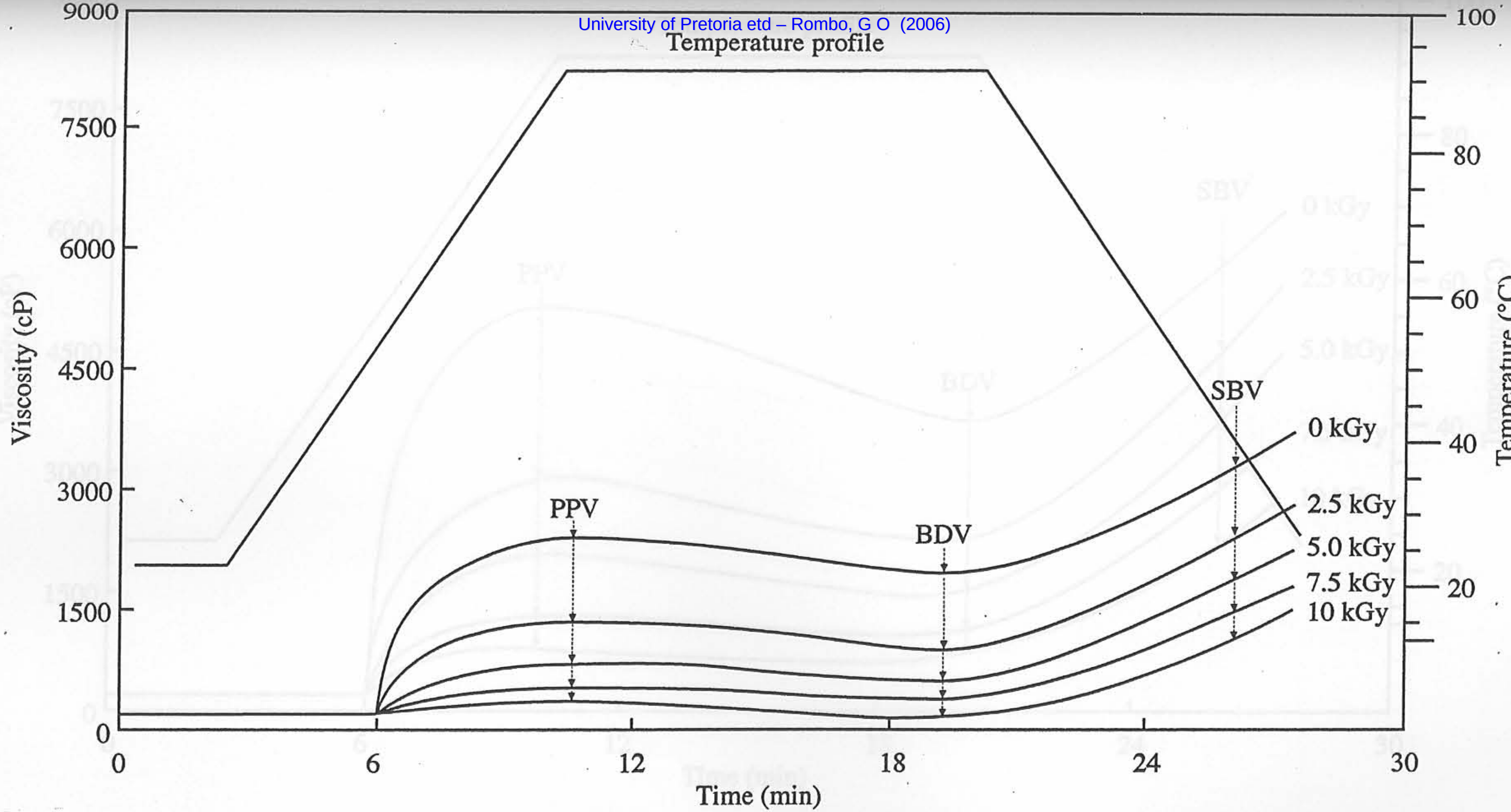

Figure 9 Schematic representation of the effects of irradiation on viscosity of porridges made from maize flour (a) at 15% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

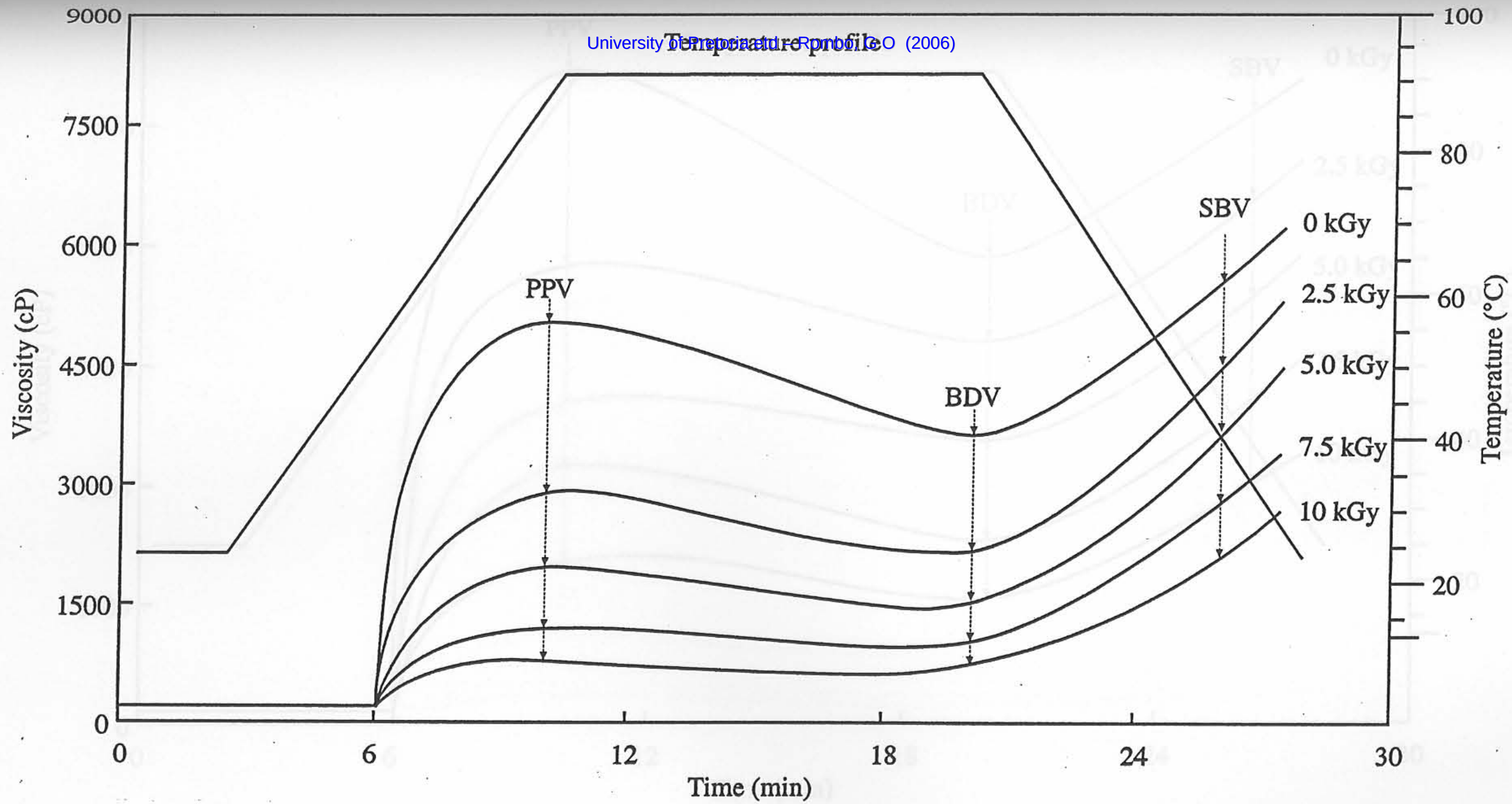

Figure 9 Schematic representation of the effects of irradiation on viscosity of porridges made from maize flour (b) at 20% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40ºC (not drawn to scale)

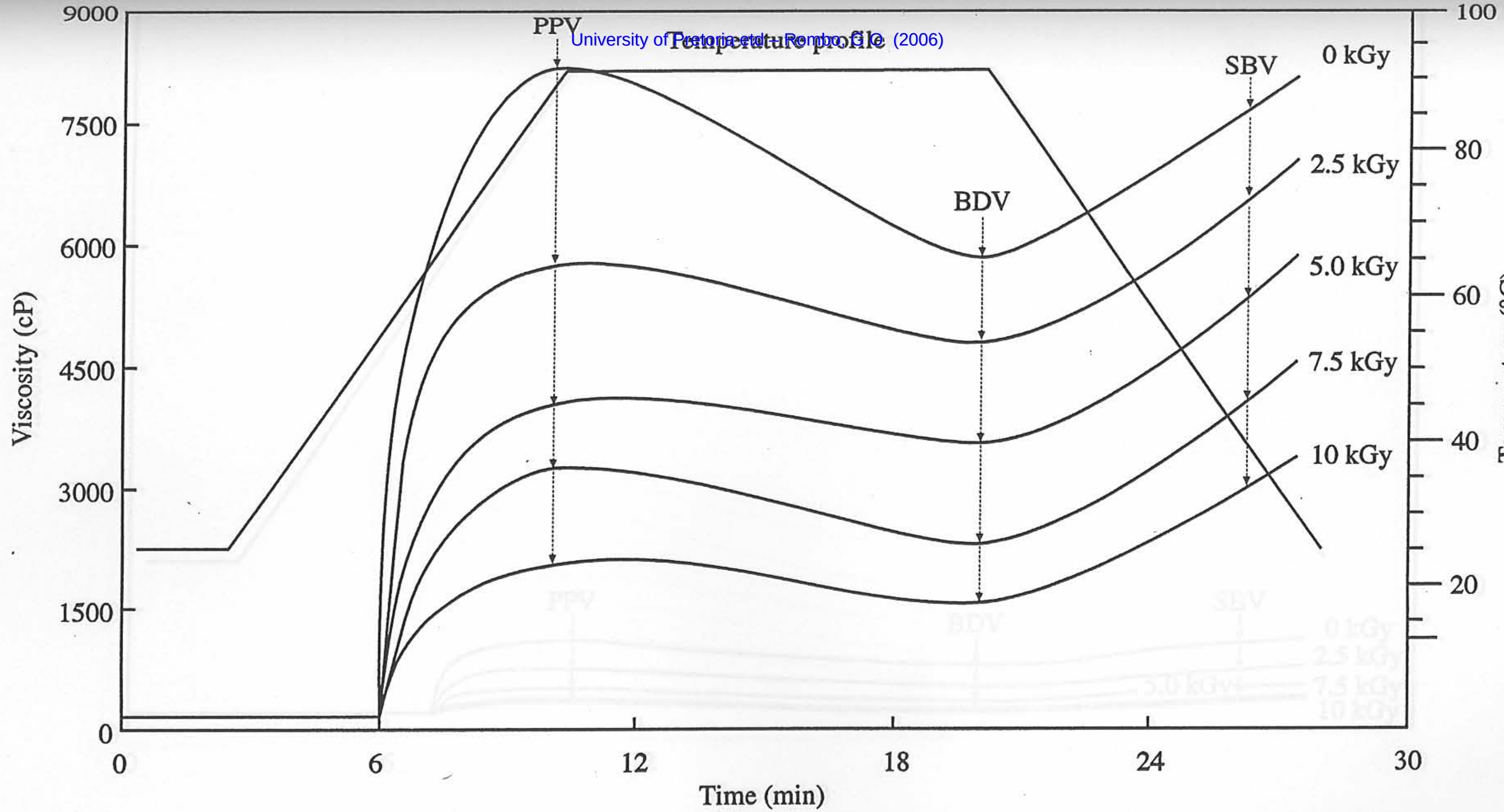

Figure 9 Schematic representation of the effects of irradiation on viscosity of porridges made from maize flour (c) at 25% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

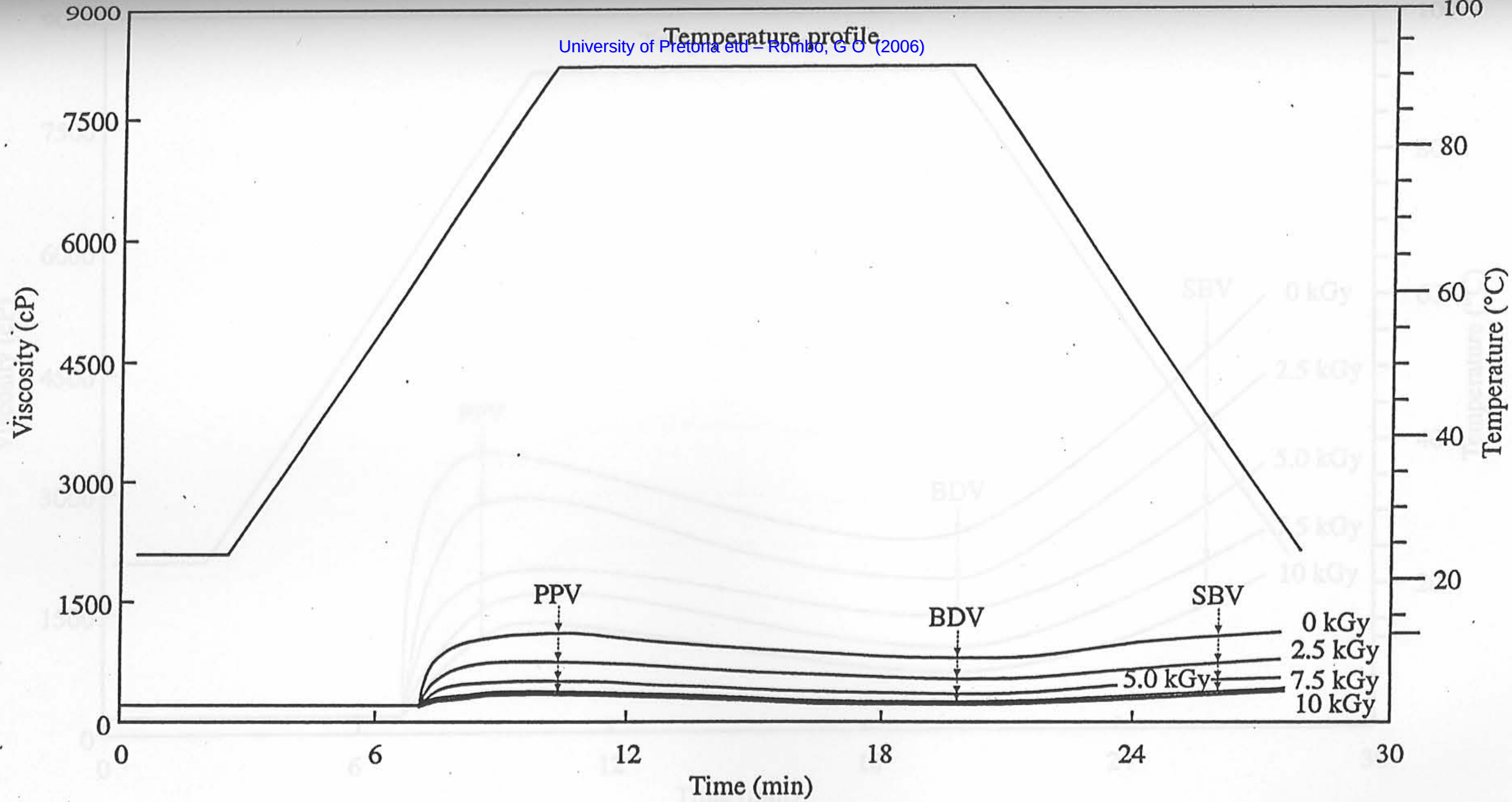

Figure 10 Schematic representation of the effects of irradiation on viscosity of porridges made from bean flour (a) at 15% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

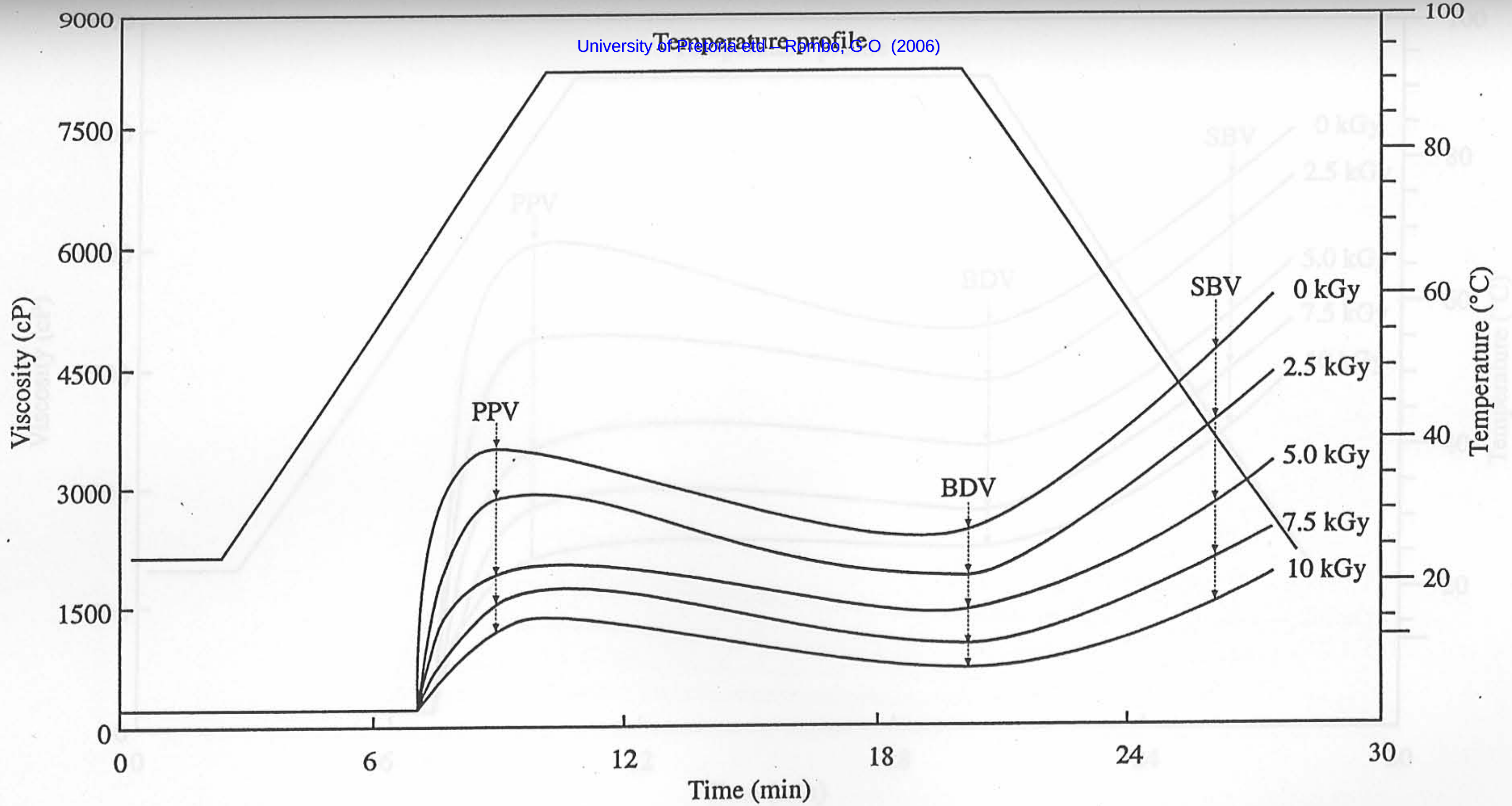

Figure 10 Schematic representation of the effects of irradiation on viscosity of porridges made from bean flour (b) at 20% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

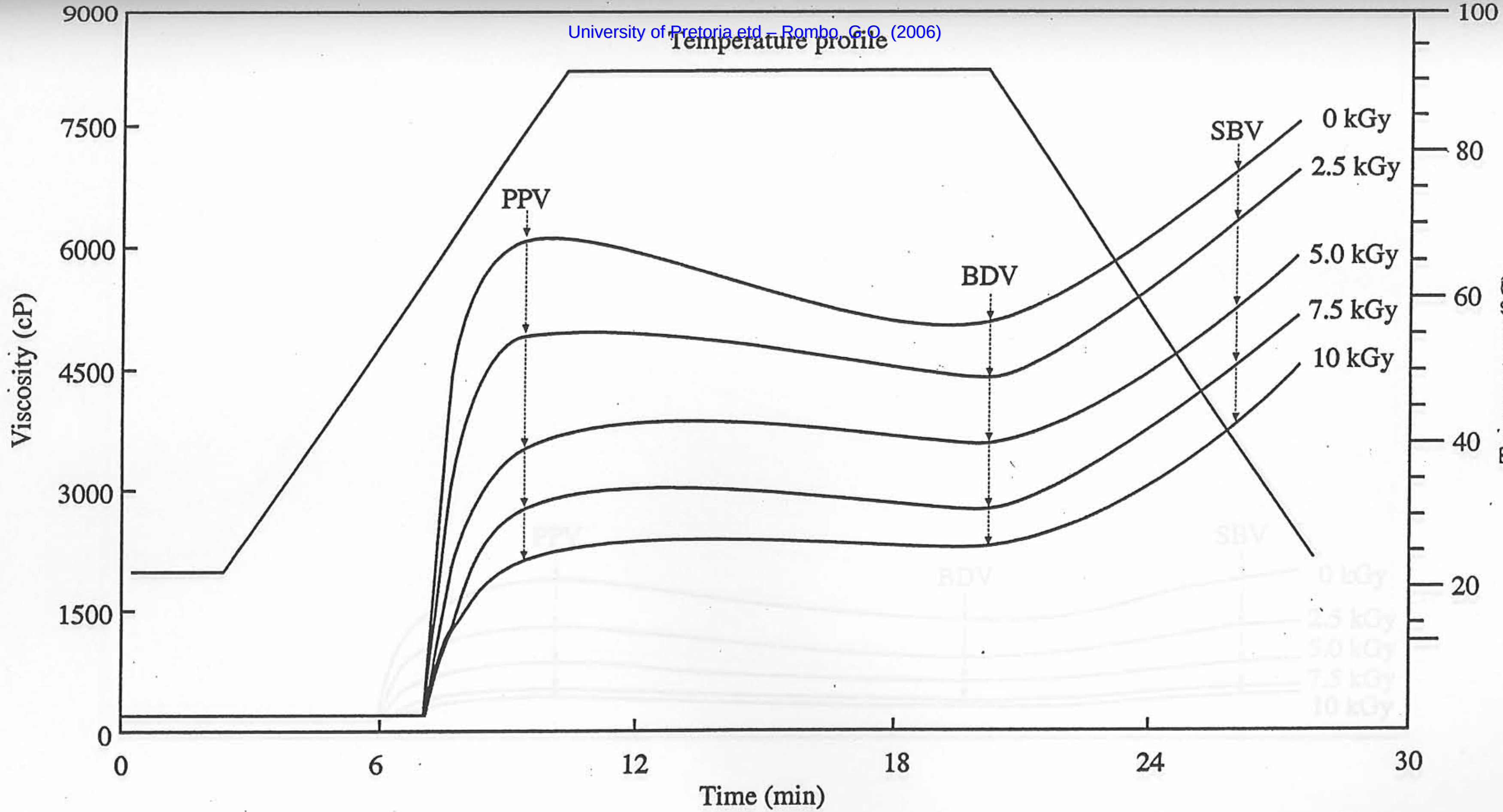

Figure 10 Schematic representation of the effects of irradiation on viscosity of porridges made from bean flour (c) at 25% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

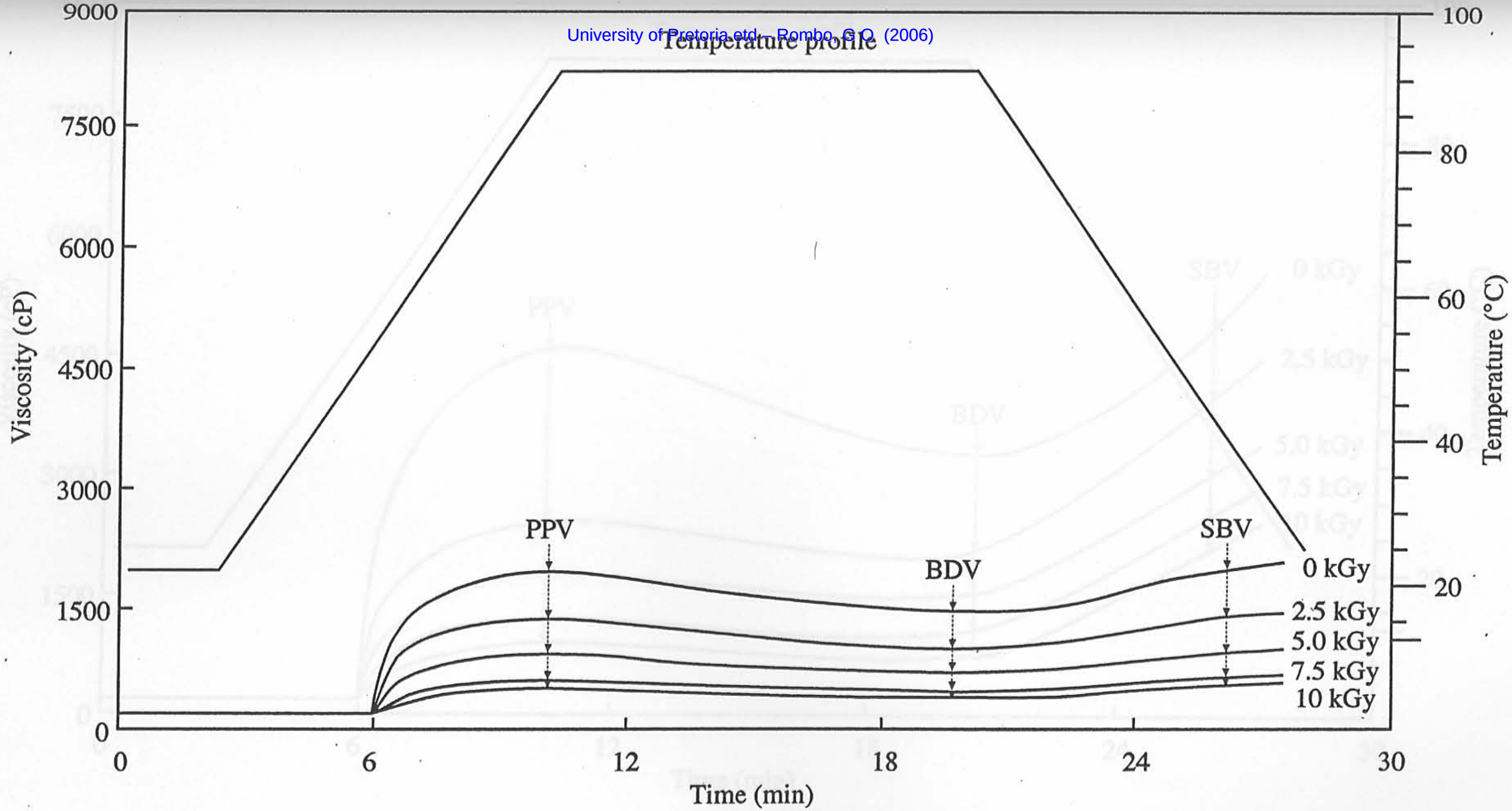

Figure 11 Schematic representation of the effects of irradiation on viscosity of porridges made from 70/30 maize:bean composite flour
(a) at 15% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

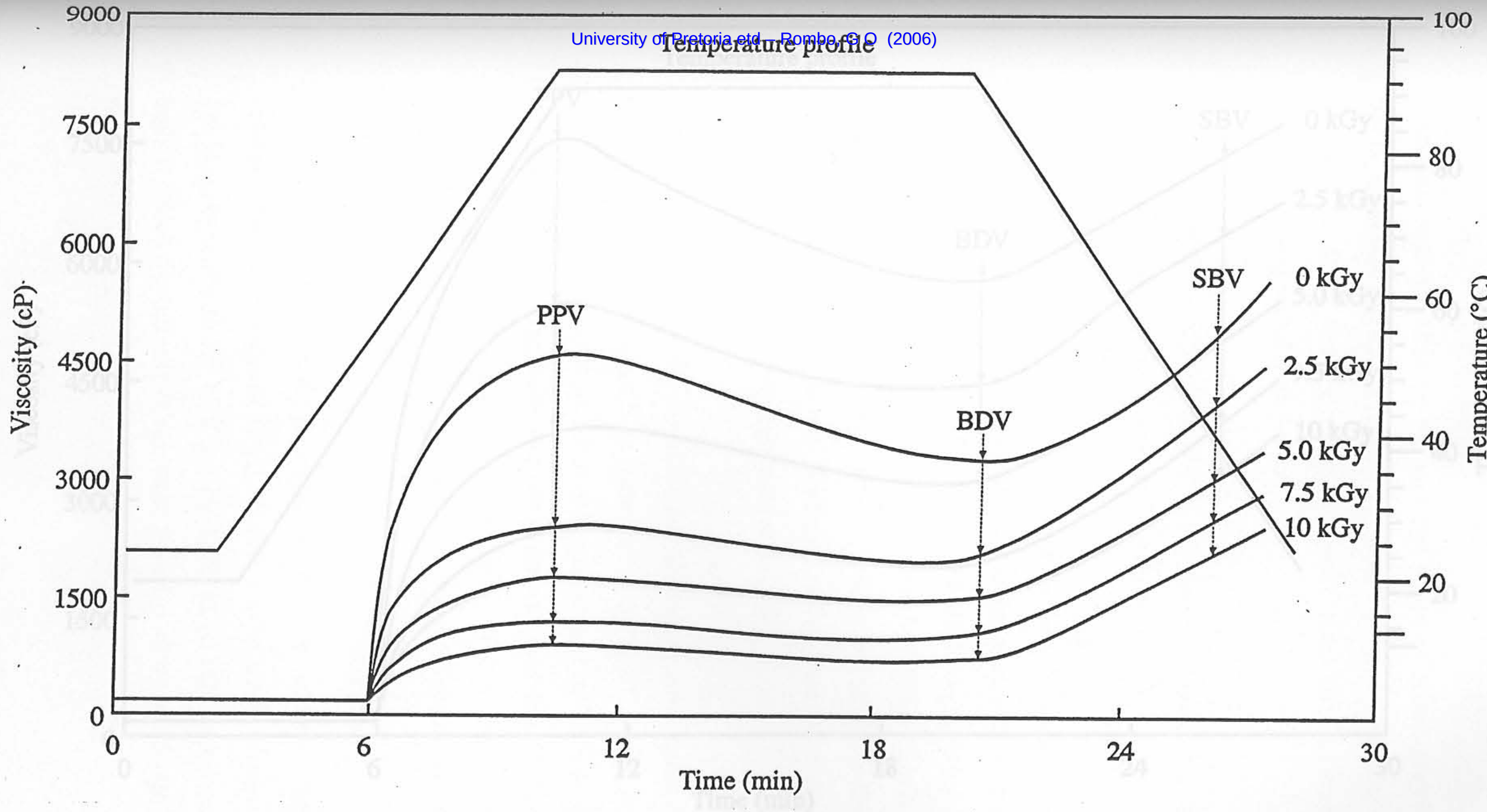

Figure 11 Schematic representation of the effects of irradiation on viscosity of porridges made from 70/30 maize:bean composite flour
(b) at 20% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

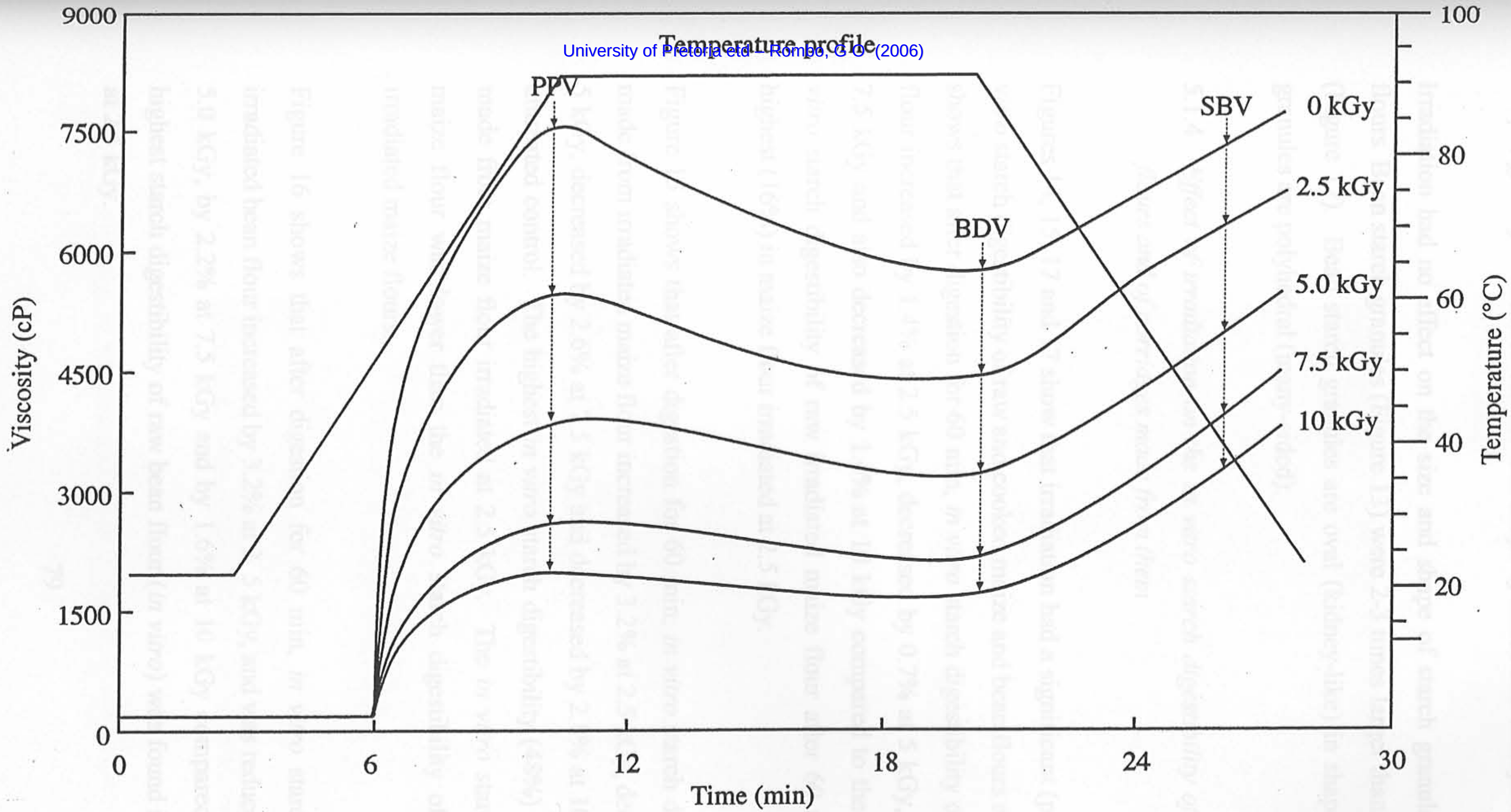

Figure 11 Schematic representation of the effects of irradiation on viscosity of porridges made from 70/30 maize:bean composite flour
(c) at 25% total solids content (w/v), PPV: peak paste viscosity, BDV: breakdown viscosity, SBV: setback viscosity at 40°C (not drawn to scale)

5.1.3 *Effect of irradiation on size and shape of maize and bean flour starch granules*

Irradiation had no effect on the size and shape of starch granules in maize and bean flours. Bean starch granules (Figure 13) were 2-3 times larger than maize starch granules (Figure 12). Bean starch granules are oval (kidney-like) in shapes while maize starch granules are polyhedral (many-sided).

5.1.4 *Effect of irradiation on the in vitro starch digestibility of raw maize and bean flours and of porridges made from them*

Figures 14, 15, 17 and 17 show that irradiation had a significant ($p \leq 0.05$) effect on the *in vitro* starch digestibility of raw and cooked maize and bean flours respectively. Figure 14 shows that after digestion for 60 min, *in vitro* starch digestibility of irradiated raw maize flour increased by 1.4% at 2.5 kGy, decreased by 0.7% at 5 kGy, decreased by 1.0% at 7.5 kGy and also decreased by 1.4% at 10 kGy compared to the untreated control. *In vitro* starch digestibility of raw irradiated maize flour after 60 min of digestion, was highest (16%) in maize flour irradiated at 2.5 kGy.

Figure 15 shows that after digestion for 60 min, *in vitro* starch digestibility of porridge made from irradiated maize flour increased by 3.2% at 2.5 kGy, decreased by 0.6% at 5 kGy, decreased by 2.6% at 7.5 kGy and decreased by 2.8% at 10 kGy compared to the untreated control. The highest *in vitro* starch digestibility (48%) was found in porridge made from maize flour irradiated at 2.5 kGy. The *in vitro* starch digestibility of raw maize flour was lower than the *in vitro* starch digestibility of porridge made from irradiated maize flours.

Figure 16 shows that after digestion for 60 min, *in vitro* starch digestibility of raw irradiated bean flour increased by 3.2% at 2. 5 kGy, and was reduced by 2.8% at 5.0 kGy, by 2.2% at 7.5 kGy and by 1.6% at 10 kGy compared to the control. The highest starch digestibility of raw bean flour (*in vitro*) was found in bean flour irradiated at 2.5 kGy.

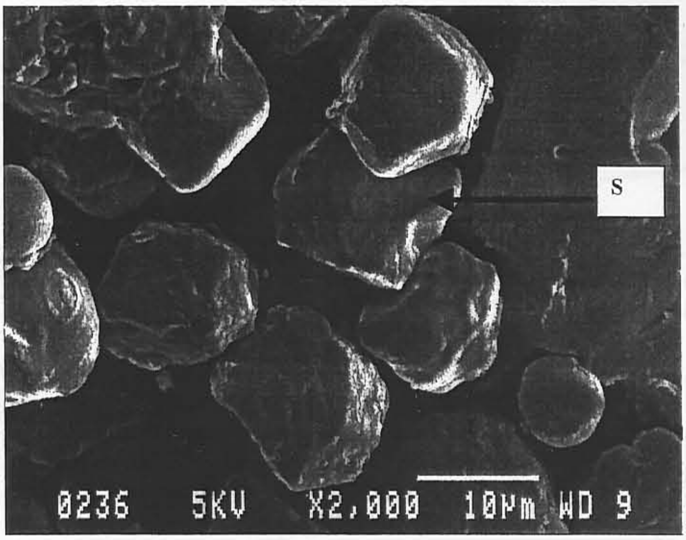

Figure 12 Size and shape of raw maize starch granule (S)

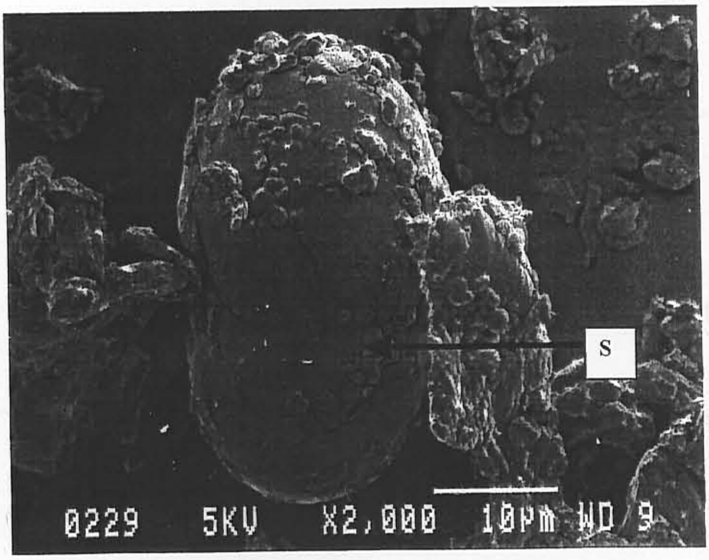

Figure 13 Size and shape of raw bean starch granule (S)

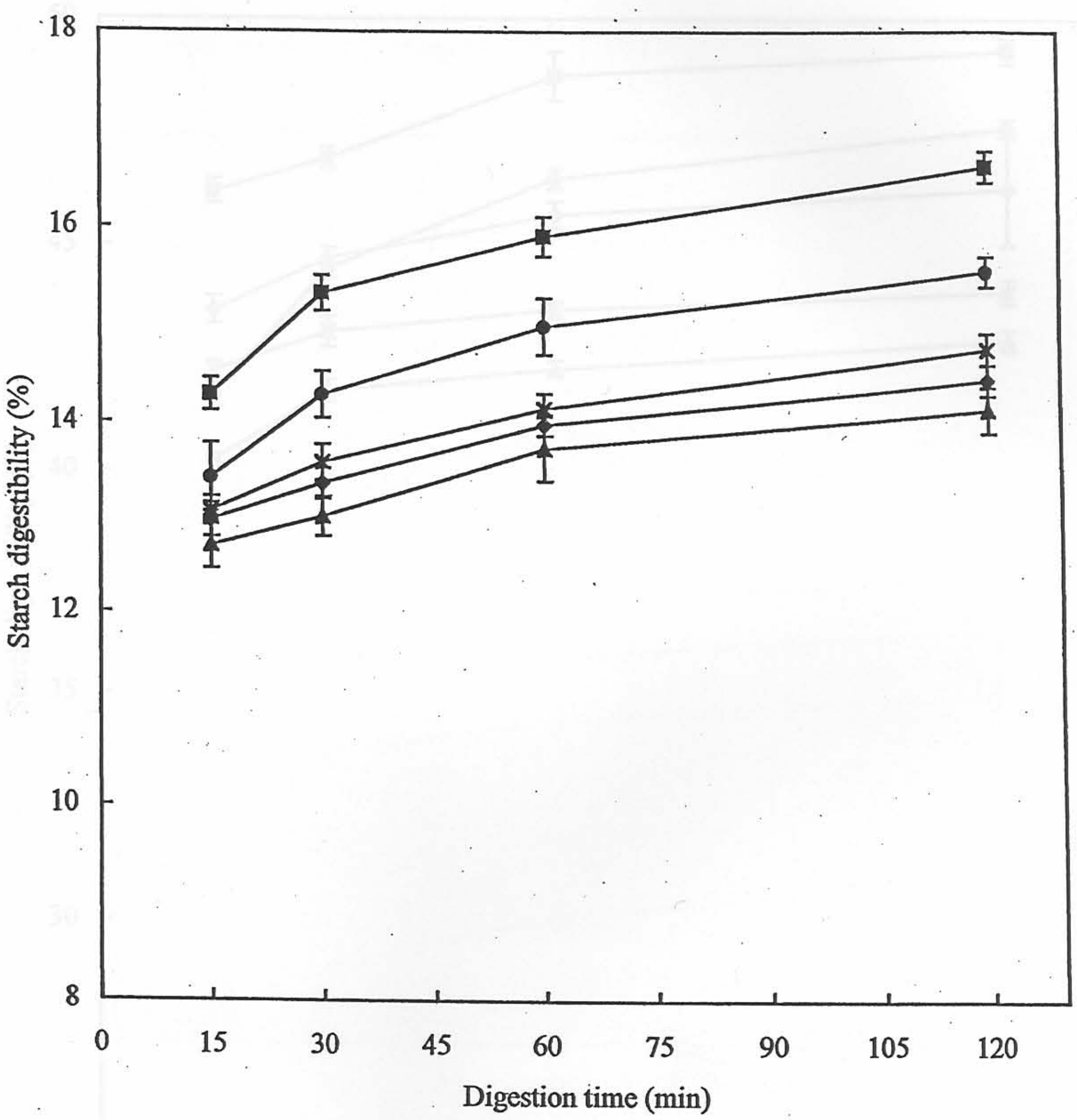

Figure 14 Effect of irradiation on *in vitro* starch digestibility of raw maize flours

—●— 0 kGy —■— 2.5 kGy —◆— 5 kGy —✕— 7.5 kGy —▲— 10 kGy

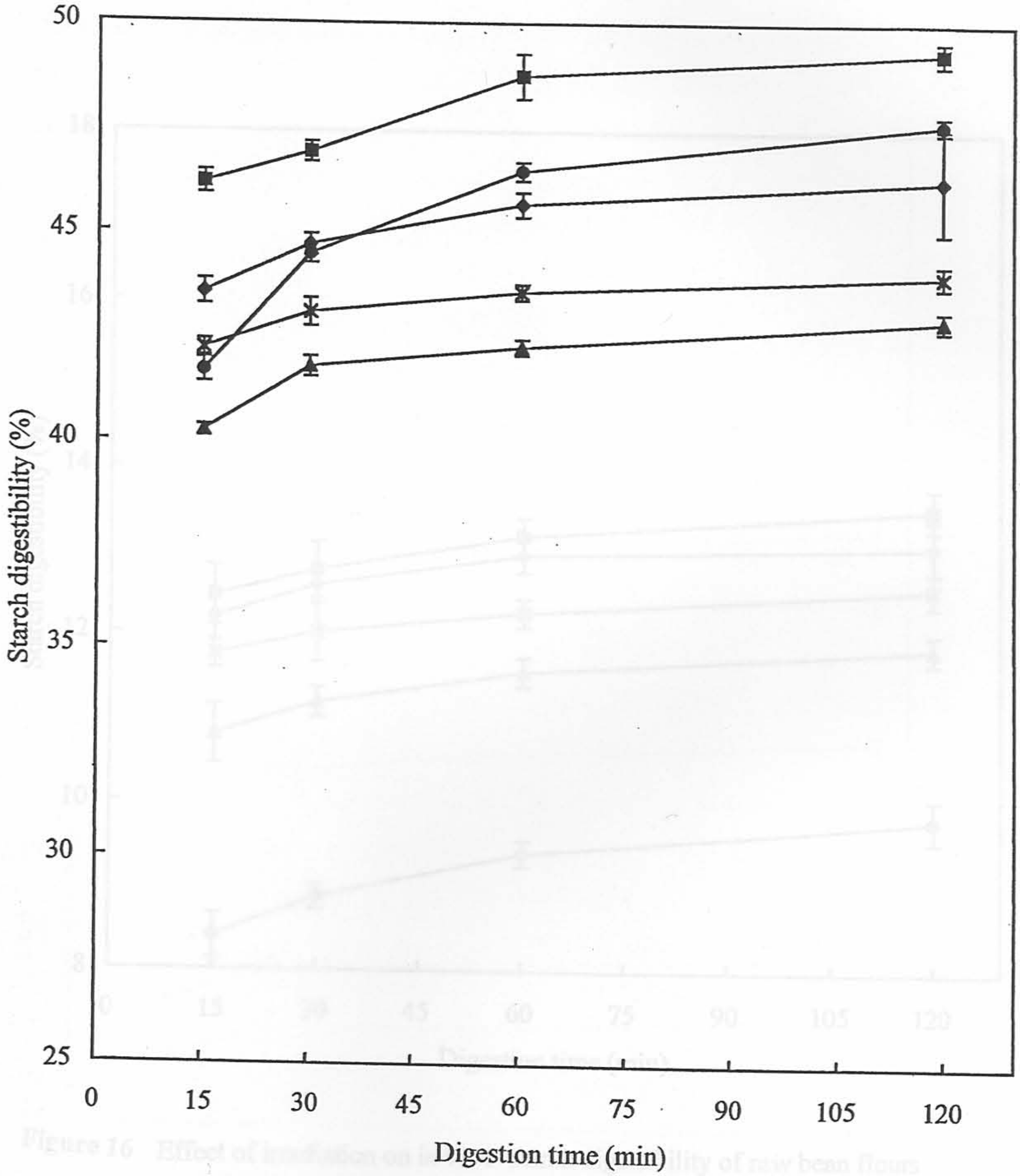

Figure 15 Effect of irradiation on *in vitro* starch digestibility of maize porridges

—●— 0 kGy —■— 2.5 kGy —◆— 5 kGy —✕— 7.5 kGy —▲— 10 kGy

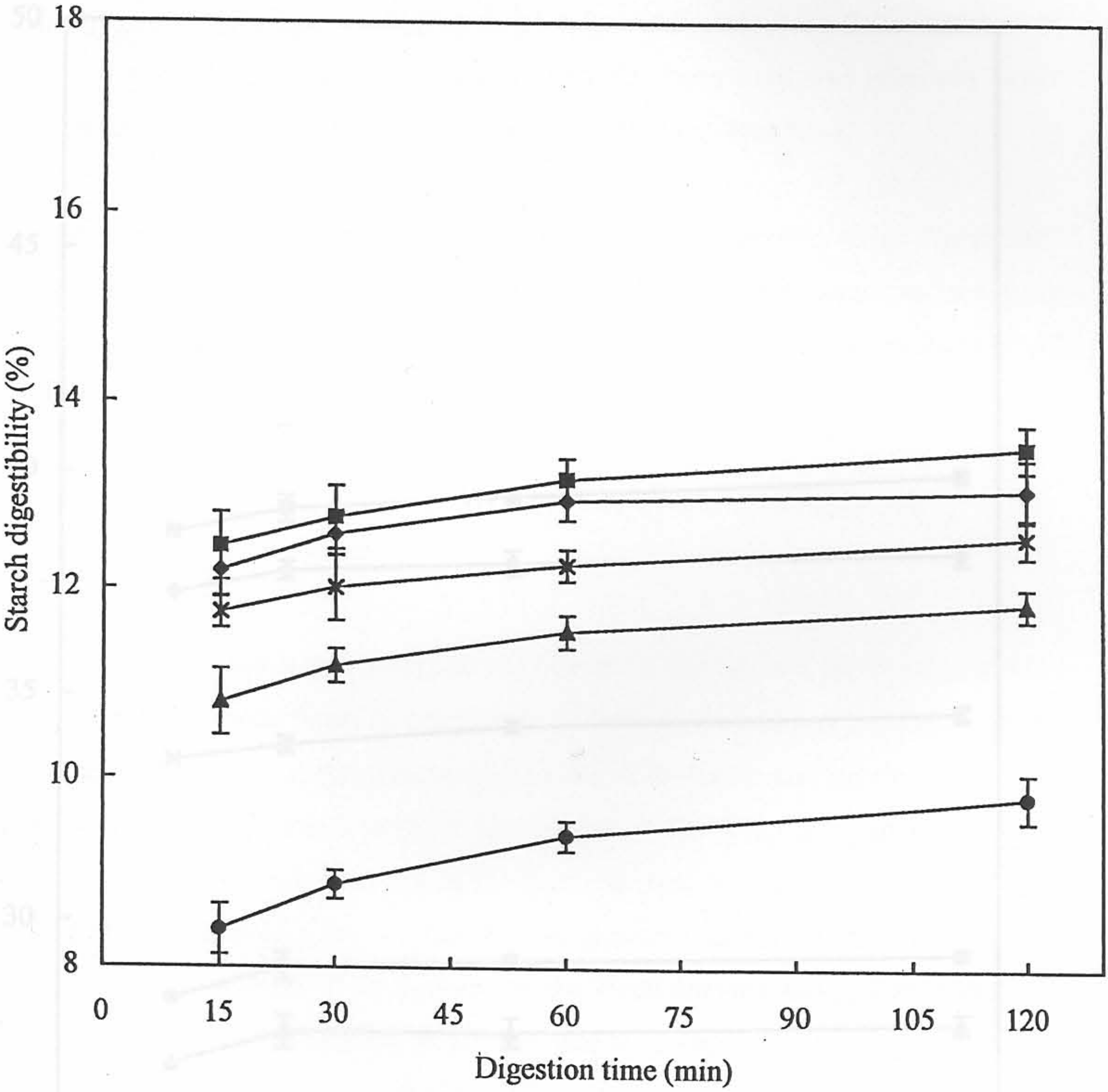

Figure 16 Effect of irradiation on *in vitro* starch digestibility of raw bean flours

—●— 0 kGy —■— 2.5 kGy —◆— 5 kGy —✕— 7.5 kGy —▲— 10 kGy

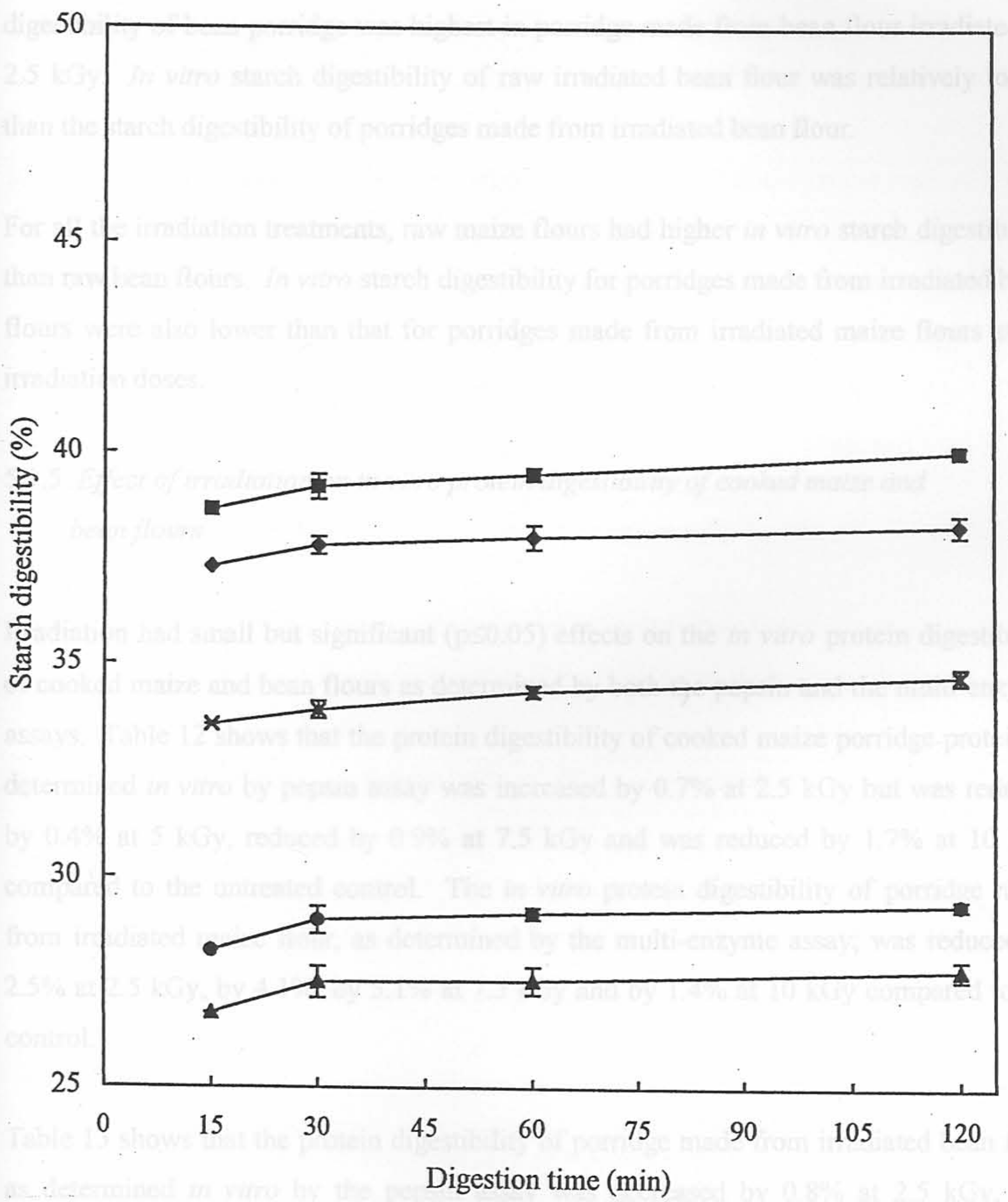

Figure 17 Effect of irradiation on *in vitro* starch digestibility of bean porridges

Figure 17 shows that after digestion for 60 min, *in vitro* starch digestibility for porridges made from irradiated bean flour increased by 8.8% at 2.5 kGy, by 7.6% at 5 kGy, by 5% at 7.5 kGy and decreased by 2.1% at 10 kGy compared to the control. *In vitro* starch digestibility of bean porridge was highest in porridge made from bean flour irradiated at 2.5 kGy. *In vitro* starch digestibility of raw irradiated bean flour was relatively lower than the starch digestibility of porridges made from irradiated bean flour.

For all the irradiation treatments, raw maize flours had higher *in vitro* starch digestibility than raw bean flours. *In vitro* starch digestibility for porridges made from irradiated bean flours were also lower than that for porridges made from irradiated maize flours at all irradiation doses.

5.1.5 *Effect of irradiation on in vitro protein digestibility of cooked maize and bean flours*

Irradiation had small but significant ($p \leq 0.05$) effects on the *in vitro* protein digestibility of cooked maize and bean flours as determined by both the pepsin and the multi-enzyme assays. Table 12 shows that the protein digestibility of cooked maize porridge protein as determined *in vitro* by pepsin assay was increased by 0.7% at 2.5 kGy but was reduced by 0.4% at 5 kGy, reduced by 0.9% at 7.5 kGy and was reduced by 1.7% at 10 kGy compared to the untreated control. The *in vitro* protein digestibility of porridge made from irradiated maize flour, as determined by the multi-enzyme assay, was reduced by 2.5% at 2.5 kGy, by 4.1%, by 5.1% at 7.5 kGy and by 1.4% at 10 kGy compared to the control.

Table 13 shows that the protein digestibility of porridge made from irradiated bean flour as determined *in vitro* by the pepsin assay was decreased by 0.8% at 2.5 kGy, was increased by 0.1% at 5.0 kGy, but was reduced by 1% at 7.5 kGy and reduced by 1.9% at 10 kGy compared to the control. The protein digestibility as determined *in vitro* by the multi-enzyme method on cooked irradiated bean flour porridge was reduced by 2.6% at

2.5 kGy, reduced by 3.6% at 5.0 kGy, reduced by 4.7% at 7.5 kGy and was reduced by 1.4% at 10 kGy compared to the control.

Table 12 Effect of irradiation on *in vitro* protein digestibility of porridge made from irradiated maize flours as determined by pepsin and multi-enzyme assays

Irradiation dose (kGy)	Pepsin method[1] (%)	Multi-enzyme method[1] (%)
0	68.5±0.47d[2]	81.8±0.37e[2]
2.5	69.2±0.10e	79.3±0.42c
5.0	68.1±0.29c	77.7±0.21b
7.5	67.6±0.21b	76.7±0.97a
10	66.8±0.18a	80.4±0.35d

[1]Values are means of three replicates determined six times ± standard deviation
[2]Mean values in a column with different letters differ significantly at p≤0.05

Table 13 Effect of irradiation *in vitro* on protein digestibility of porridge made from irradiated bean flours as determined by pepsin and multi-enzyme assays

Irradiation dose (kGy)	Pepsin method[1] (%)	Multi-enzyme method[1] (%)
0	66.1±0.66c[2]	81.8±0.37e[2]
2.5	65.3±0.11b	79.2±0.42c
5.0	66.2±0.05c	78.2±0.66b
7.5	65.1±0.78b	77.1±1.18a
10	64.2±0.70a	80.4±0.35d

[1]Values are means of three replicates determined six times ± standard deviation
[2]Mean values in a column with different letters differ significantly at p≤0.05

5.2 Phase 2 Effect of irradiation on molecular properties of maize and bean flours and on their starches that may be responsible for decreases in their starch digestibility *in vitro* at doses higher than 2.5 kGy

In Phase 2, tests were performed to determine whether there were molecular changes in the irradiated maize and bean flours that may be responsible for the increase and decrease in *in vitro* starch digestibility. Colour measurements were performed on maize and bean flours after irradiation at 0, 5, 10, 20 and 40 kGy. Changes in the β-bonded starch content of maize and bean flours irradiated at 0, 5, 10, 20 and 40 kGy were also determined. The effect of irradiation on the degree of gelatinisation was determined using differential scanning calorimetry (DSC). The molecular weight distributions of starch molecules in irradiated maize and bean flours were determined using size exclusion high performance liquid chromatography (HPLCSEC).

5.2.1 *Effect of irradiation on the colour of maize and bean flours*

Irradiation caused significant ($p \leq 0.05$) changes in the L, a and b values of maize flours. The L values of maize flour were decreased by irradiation, while the a and b values were increased with the increasing dose of irradiation (Table 14).

Irradiation had significant ($p \leq 0.05$) effect on the L, a and b values of bean flour. As the irradiation dose increased the L values were decreased. However, the a and b values of bean flour were increased by the irradiation dose (Table 15).

Tables 14 and 15 show that there were slightly greater changes in the L values of maize flour than bean flour with increases in irradiation dose. However, there were slightly greater changes in a values of bean flour than maize flour with the increases in irradiation dose. The b values of both maize and bean flours were changed similarly by increases in irradiation dose.

Table 14 Effect of irradiation on L[3], a[4] and b[5] values of maize flours

Irradiation dose (kGy)	L[1]	a[1]	b[1]
0	83.6±1.2d[2]	-0.3±0.5a	11.5±0.4a
5	80.5±0.1c	0.2±0.04b	11.8±0.1a
10	80.1±0.2c	0.4±0.1bc	12.6±0.1b
20	78.9±0.8b	0.6±0.04c	13.3±0.1c
40	77.4±0.6a	1.2±0.2d	14.8±0.6d

[1]Values are mean of three replicates determined six times ± standard deviation
[2]Values in the same column followed by different letters differ significantly at $p \leq 0.05$
[3]L values: Degree of lightness (White $^{+}100 \leftarrow\rightarrow 0$ Black)
[4]a values: Degree of redness (red $^{+}100 \leftarrow\rightarrow {}^{-}80$ green)
[5]b values: Degree of yellowness (yellow $^{+}100 \leftarrow\rightarrow {}^{-}80$ blue)

Table 15 Effect of irradiation on the L[3], a[4] and b[5] values of bean flours

Irradiation dose (kGy)	L[1]	a[1]	b[1]
0	84.8±0.2e[2]	-1.1±0.1a	7.7±0.03a
5	83.7±0.2d	0.3±0.02b	8.7±0.1b
10	83.2±0.1c	0.4±0.03bc	9.8±0.1c
20	82.3±0.1b	0.6±0.02cd	10.5±0.1d
40	80.8±0.4a	0.7±0.02d	11.2±0.1e

[1]Values are mean of three replicates determined six times ± standard deviation
[2]Values in the same column followed by different letters differ significantly at $p \leq 0.05$
[3]L values: Degree of lightness (White $^{+}100 \leftarrow\rightarrow 0$ Black)
[4]a values: Degree of redness (red $^{+}100 \leftarrow\rightarrow {}^{-}80$ green)
[5]b values: Degree of yellowness (yellow $^{+}100 \leftarrow\rightarrow {}^{-}80$ blue)

5.2.2 *Effect of irradiation on the β(1-3) and β(1-4) -bonded starch contents of starches isolated from maize and bean flours*

Irradiation caused small but significant ($p \leq 0.05$) changes in the β-bonded starch content of starches isolated from irradiated maize and bean flours compared to the untreated controls. The β-bonded starch content in isolated starches increased with irradiation dose for both maize and bean flours. More β-bonded starch was formed in irradiated bean flour than from maize flour at any given irradiation dose (Figure 18).

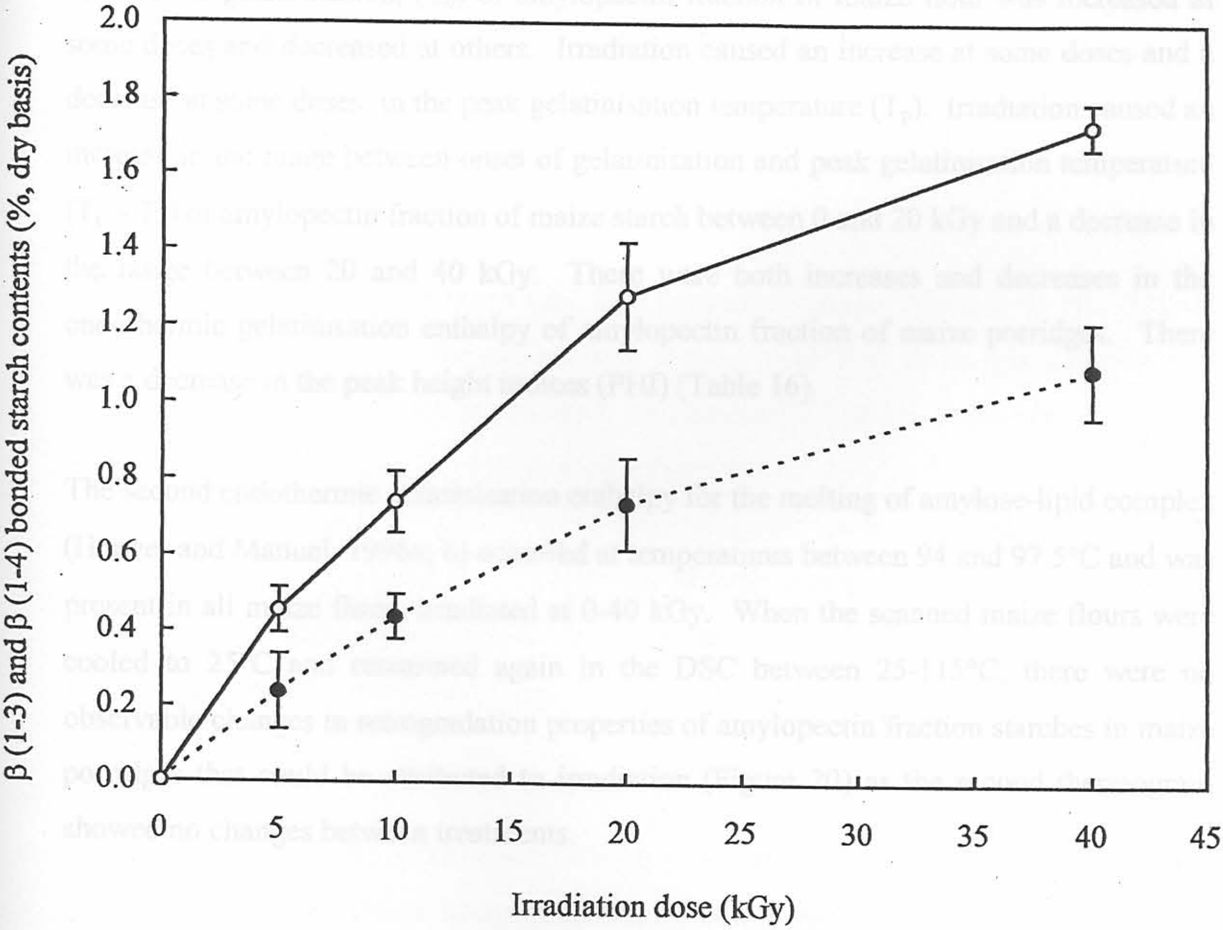

Figure 18 The β(1-3) and β(1-4)- bonded starch contents of starches isolated by wet milling from irradiated maize and bean flours

- - ● - - The β (1-3) and β (1-4) bonded starch contents of irradiated maize flour starch

—○— The β (1-3) and β (1-4) bonded starch contents of irradiated bean flour starch

5.2.3 *Effect of irradiation on thermal properties of amylopectin fraction of maize and bean flour starches*

Irradiation caused changes in the thermal properties of starches in maize and bean flours as determined by differential scanning calorimetry (DSC). The first scanning thermogram shows the effects of irradiation on the thermal properties of the amylopectin fraction of maize flour (Figure 19). As shown in Table 16 and Figure 19, the temperature of onset of gelatinisation, (T_o) of amylopectin fraction of maize flour was increased at some doses and decreased at others. Irradiation caused an increase at some doses and a decrease at some doses in the peak gelatinisation temperature (T_p). Irradiation caused an increase in the range between onset of gelatinisation and peak gelatinisation temperature ($T_p - T_o$) of amylopectin fraction of maize starch between 0 and 20 kGy and a decrease in the range between 20 and 40 kGy. There were both increases and decreases in the endothermic gelatinisation enthalpy of amylopectin fraction of maize porridges. There was a decrease in the peak height indices (PHI) (Table 16).

The second endothermic gelatinisation enthalpy for the melting of amylose-lipid complex (Hoover and Manuel, 1996a; b) occurred at temperatures between 94 and 97.5°C and was present in all maize flours irradiated at 0-40 kGy. When the scanned maize flours were cooled to 25°C and rescanned again in the DSC between 25-115°C, there were no observable changes in retrogradation properties of amylopectin fraction starches in maize porridges that could be attributed to irradiation (Figure 20) as the second thermogram showed no changes between treatments.

Table 16 Effect of irradiation on thermal properties of amylopectin fractions of maize flour

Irradiation dose (kGy)	To[1] (°C)	Tp[2] (°C)	Tp– To (°C)	ΔH[3] (J/g)	PHI[4] (J/°C) ΔH/ Tp– To
0	63.5	71.8	8.3	10.21	1.23
5	63.9	72.4	8.5	10.29	1.21
10	63.2	72.1	8.9	9.28	1.04
20	62.8	72.4	9.6	10.58	1.10
40	62.83	72.1	9.3	9.20	0.99

[1] T_o is the onset temperature of endothermic gelatinisation enthalpy
[2] T_p is the peak temperature of the endothermic gelatinisation enthalpy
[3] ΔH is the endothermic gelatinisation enthalpy
[4] PHI is the Peak Height Index

Table 17 and Figure 21 show clearly that irradiation caused changes in the thermal properties of amylopectin fraction of bean flours. The first thermogram shows that irradiation caused an increase in the onset temperature (T_o) of gelatinisation. Irradiation also caused an increase in the peak gelatinisation temperature (T_p) (Table 17). Irradiation caused a reduction in the range between onset of gelatinisation and peak gelatinisation temperature ($T_p - T_o$) of amylopectin fraction of bean starch. Irradiation also caused an increase in the endothermic gelatinisation enthalpy of amylopectin fractions of bean flours. The peak height indices of amylopectin fraction of bean flours were increased consistently (Table 17).

The second endothermic gelatinisation enthalpy for the melting of amylose-lipid complex (Hoover and Manuel, 1996a; b) occurred at temperatures between 94 and 97.5°C and was present in all bean flours irradiated at 0-40 kGy. When the scanned bean flours were cooled to 25°C and rescanned again in the DSC between 25-1115°C, there were no observable changes in retrogradation properties of amylopectin fraction starches in bean porridges that could be attributed to irradiation (Figure 22) as the second thermogram showed no changes between treatments.

Table 17 Effect of irradiation on thermal properties of amylopectin fractions of bean flour

Irradiation dose (kGy)	To[1] (°C)	Tp[2] (°C)	Tp– To (°C)	ΔH[3] (J/g)	PHI[4] (J/°C) ΔH/Tp–To
0	67.0	75.5	8.5	4.60	0.54
5	67.5	75.5	8.0	5.65	0.71
10	68.0	75.9	7.9	8.71	1.10
20	69.4	76.2	6.8	9.50	1.40
40	71.2	76.5	5.3	9.00	1.70

[1] T_o is the onset temperature of gelatinisation,
[2] T_p is the peak temperature of the gelatinisation endotherm
[3] ΔH is the endothermic gelatinisation enthalpy
[4] PHI is the Peak Height Index

5.2.4 *Effect of irradiation on the molecular weight distribution of maize and bean flour starches*

Both maize and bean flours starches had four fractions as determined by high performance liquid size exclusion chromatography (HPLCSEC) using pullulan standards for the determination of molecular weight as shown in Figures 24 and 25. In maize the largest fraction had an average molecular weight of 4×10^6 Da, the second fraction had an average molecular weight of 4×10^5 Da. The third fraction had an average molecular weight of 2×10^5 Da. The fourth fraction had an average molecular weight of 2×10^3 Da (Figure 23).

The amount of the first fraction of maize flour starch was reduced with increases in irradiation dose. The first fraction of maize starches decreased with increasing irradiation doses while the second, third and fourth fractions increased with irradiation doses.

Bean starch had four fractions as determined by HPLCSEC using pullulan standards for determination of the molecular weight. The first had an average molecular weight of 3×10^6 Da. The second fraction (normally referred to as intermediate molecular weight starch fraction) had an average molecular weight of 4×10^5 Da. The third fraction had an average molecular weight of 4×10^4 Da. The fourth fraction had an average molecular weight of 1×10^3 Da (Figure 24). A similar trend was observed for starch from the irradiated bean flour (Figure 24). However, the reductions in amount of the amylopectin fraction with irradiation dose were higher in bean flour starch compared to that of maize flour starch.

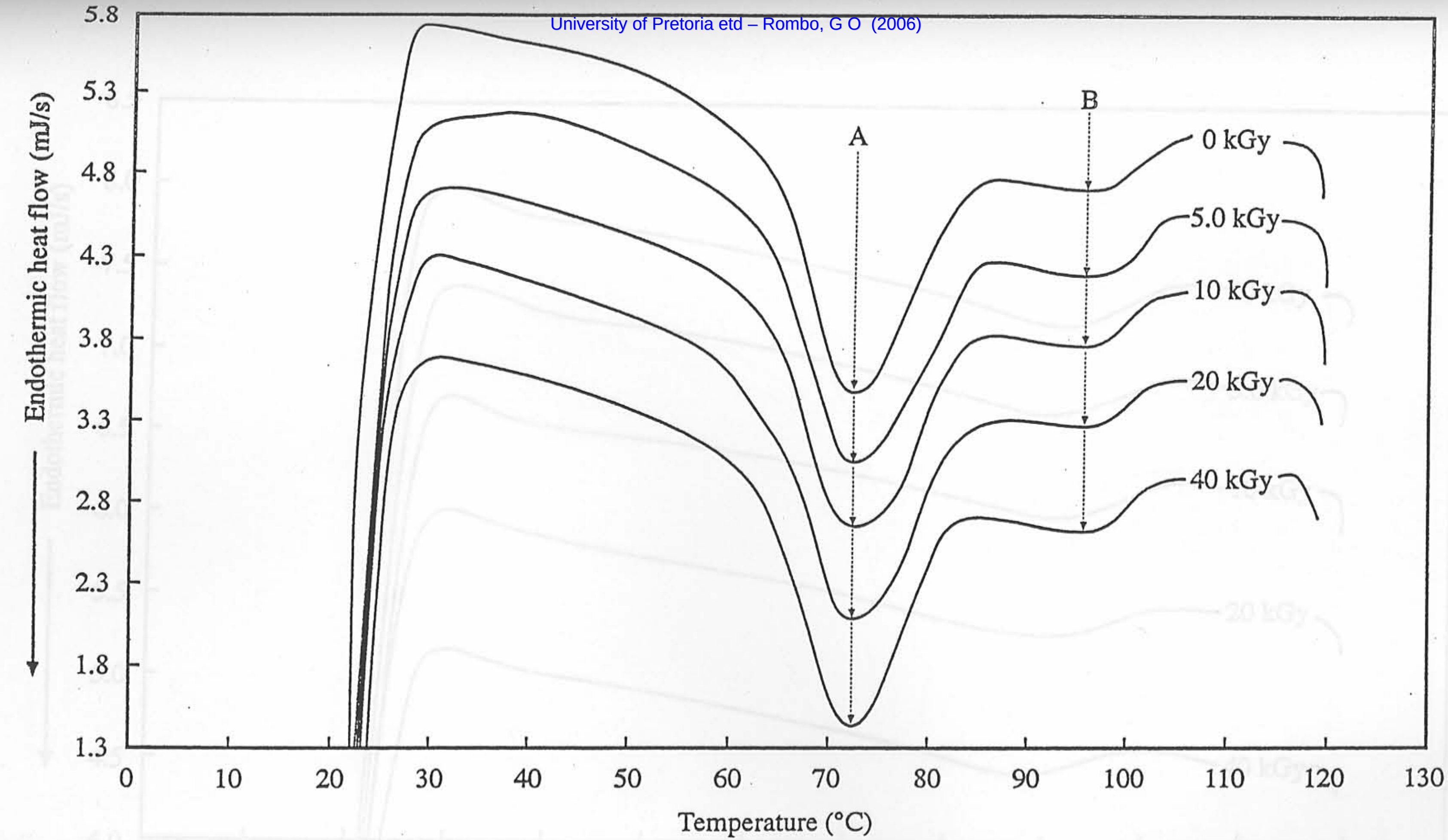

Figure 19 Effect of irradiation on gelatinisation properties of amylopectin in porridges made from maize flours
A: the endothermic gelatinisation enthalpy of amylopectin.
B: the endothermic melting enthalpy of amylose-lipid complex.

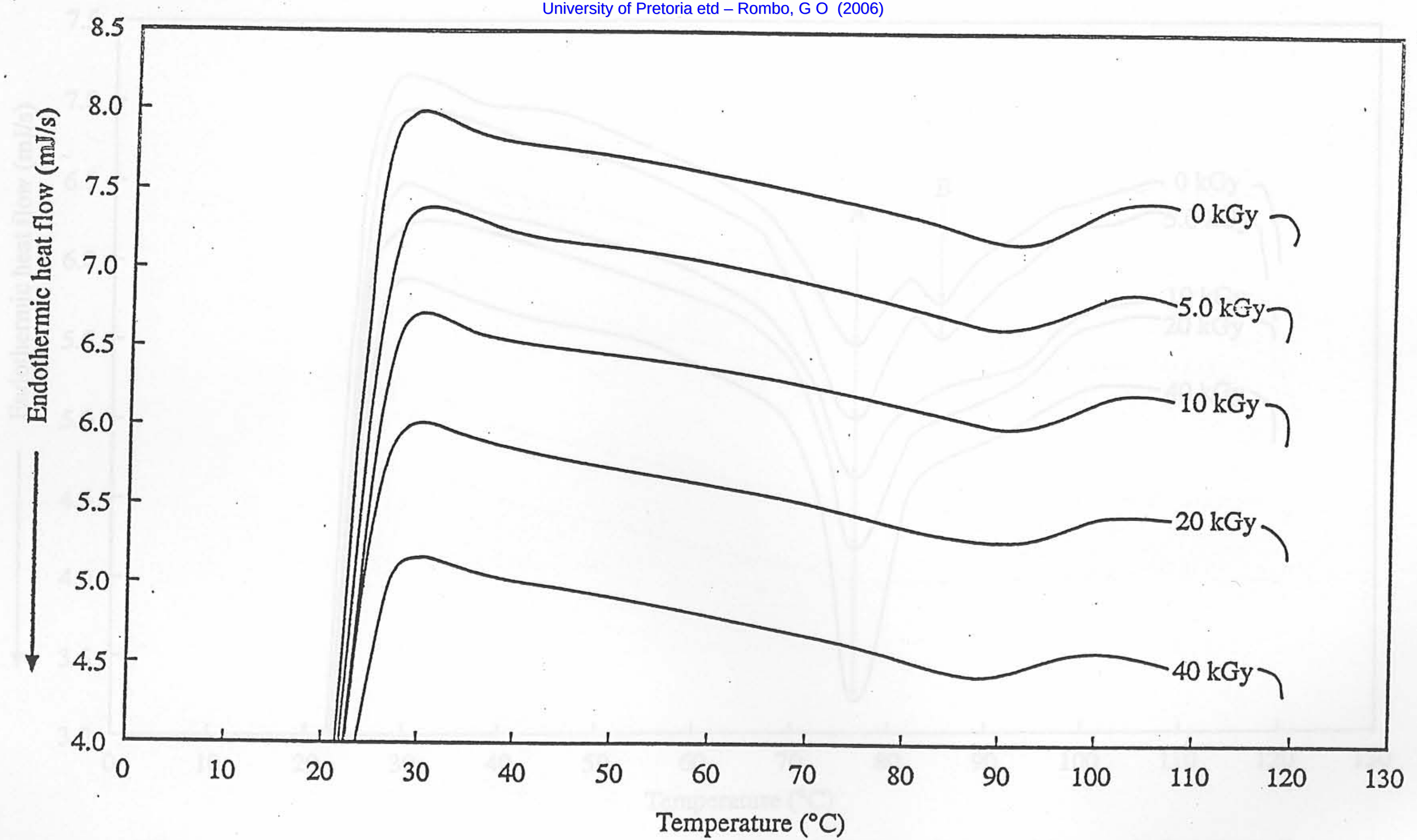

Figure 20 Effect of irradiation on retrogradation properties of amylopectin in porridges made from maize flours

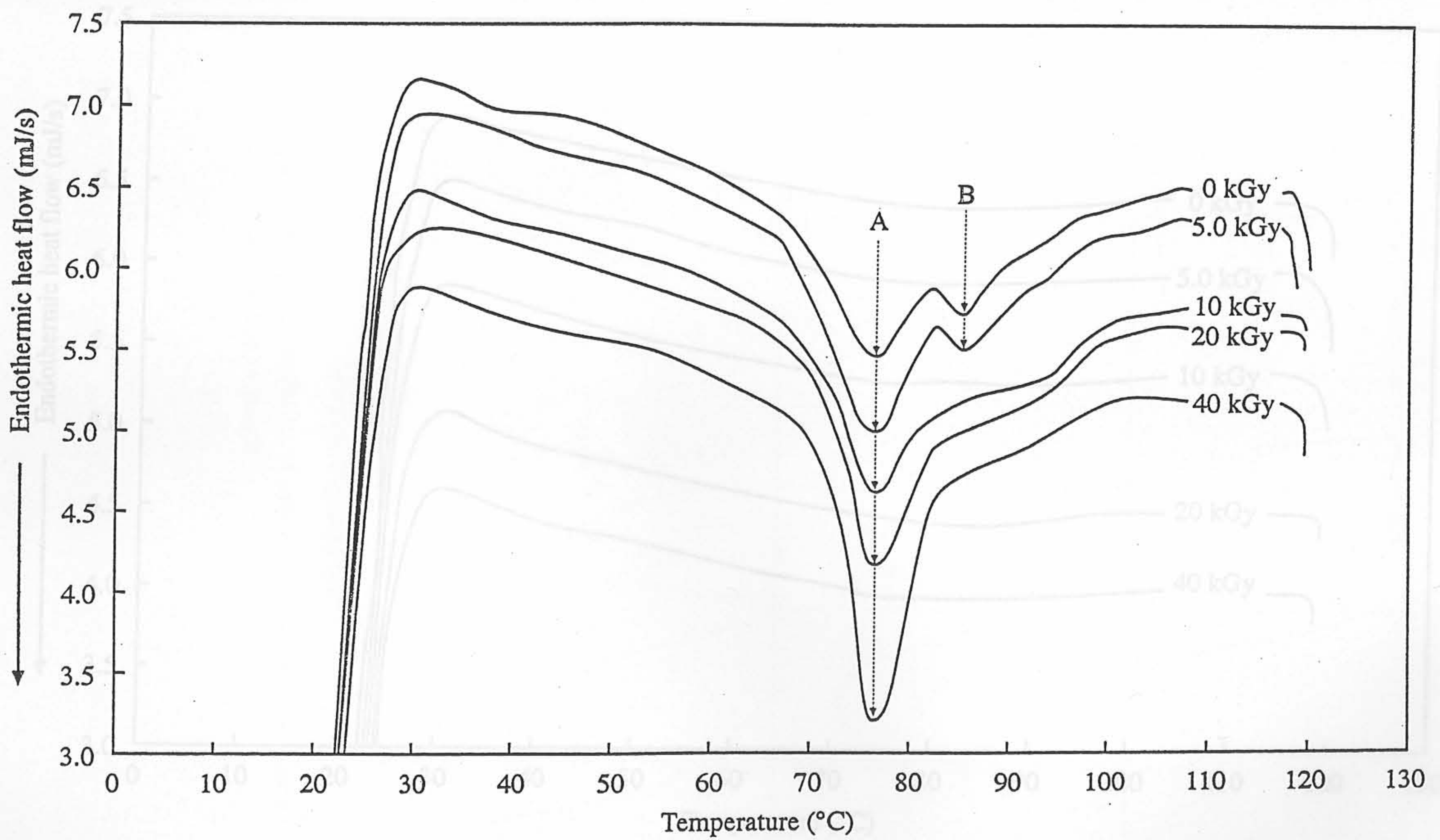

Figure 21 Effect of irradiation on gelatinisation properties of amylopectin in porridges made from bean flours
A: the endothermic gelatinisation enthalpy of amylopectin.
B: the endothermic melting enthalpy of amylose-lipid complex

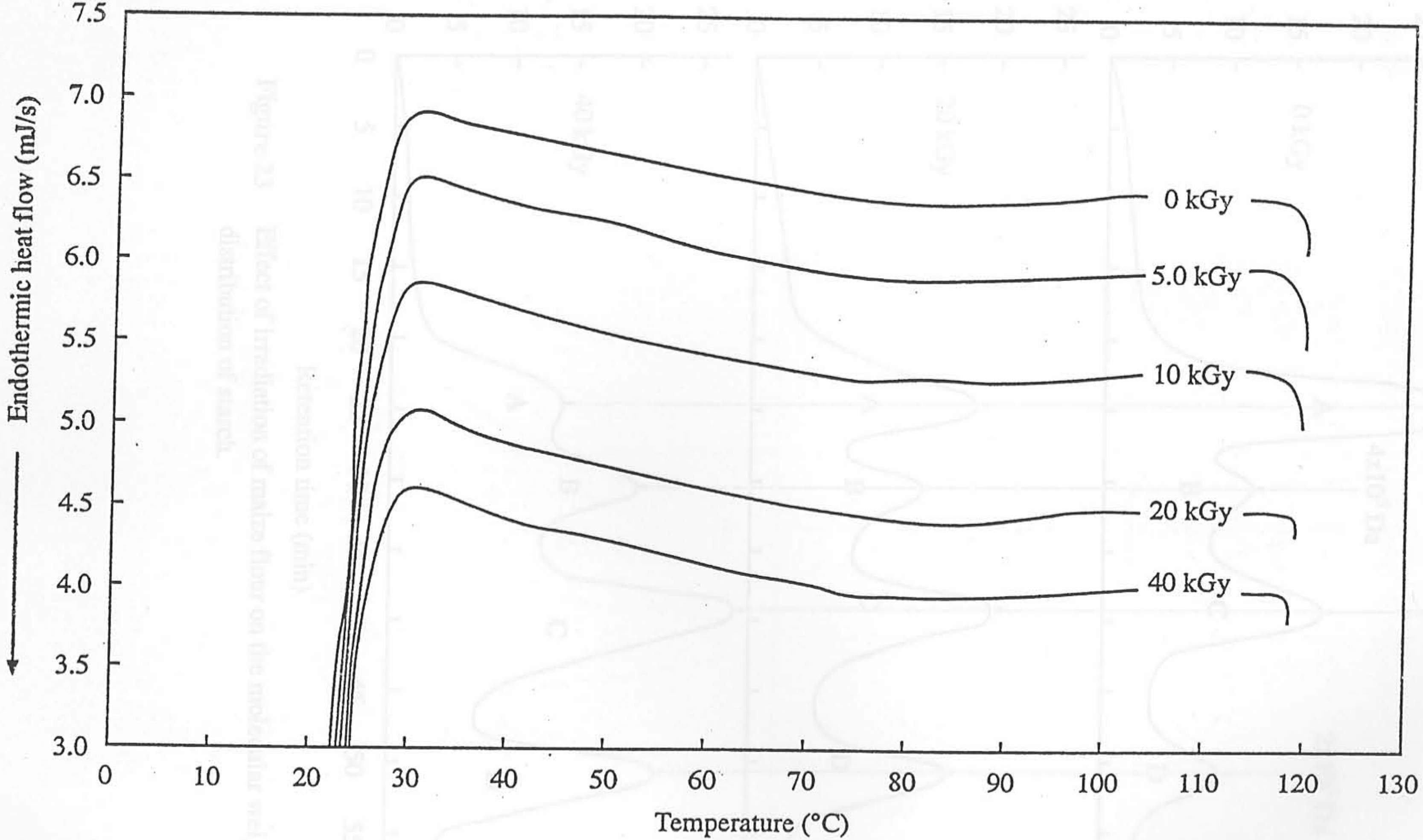

Figure 22 Effect of irradiation on retrogradation properties of amylopectin in porridges made from bean flours

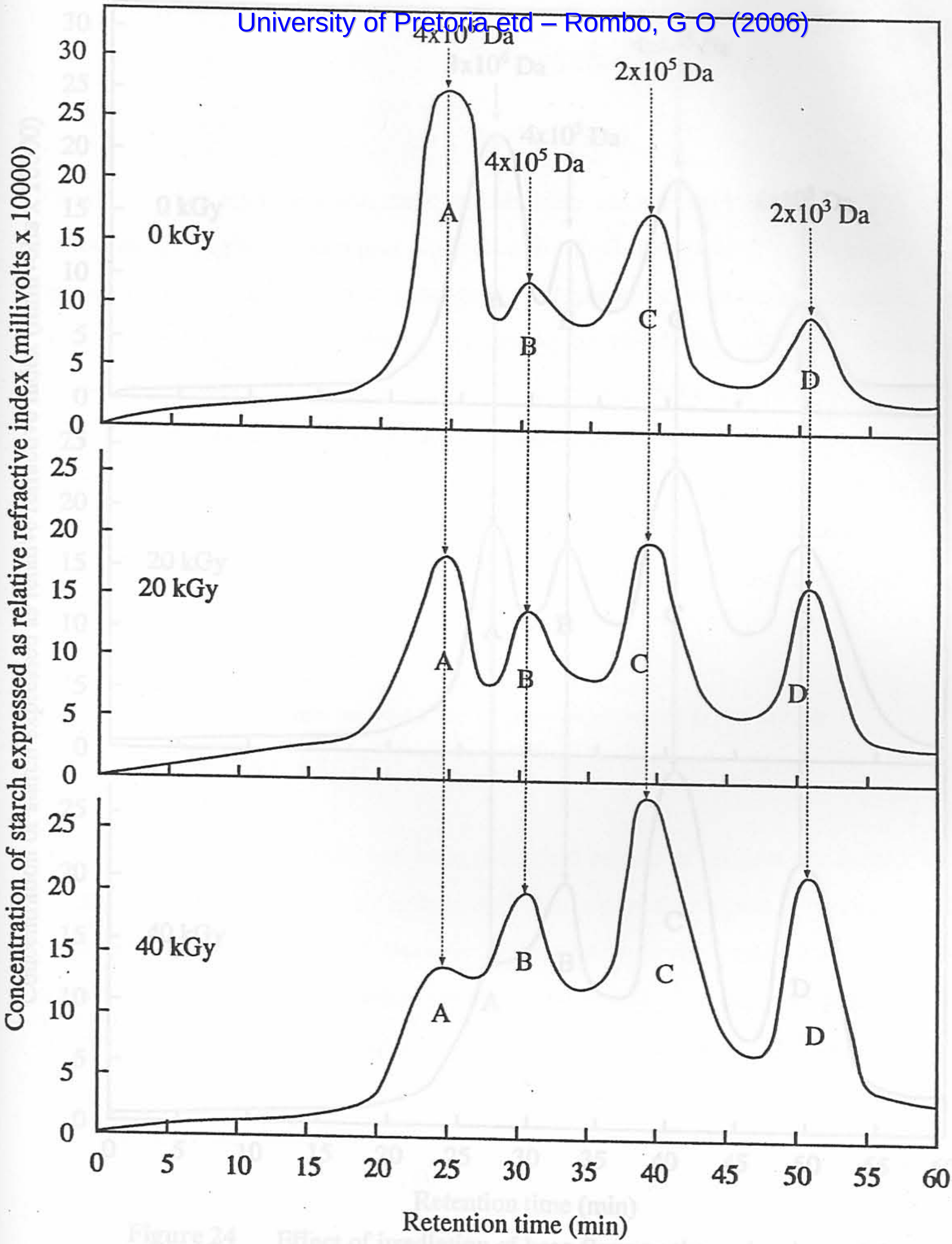

Figure 23 Effect of irradiation of maize flour on the molecular weight distribution of starch.

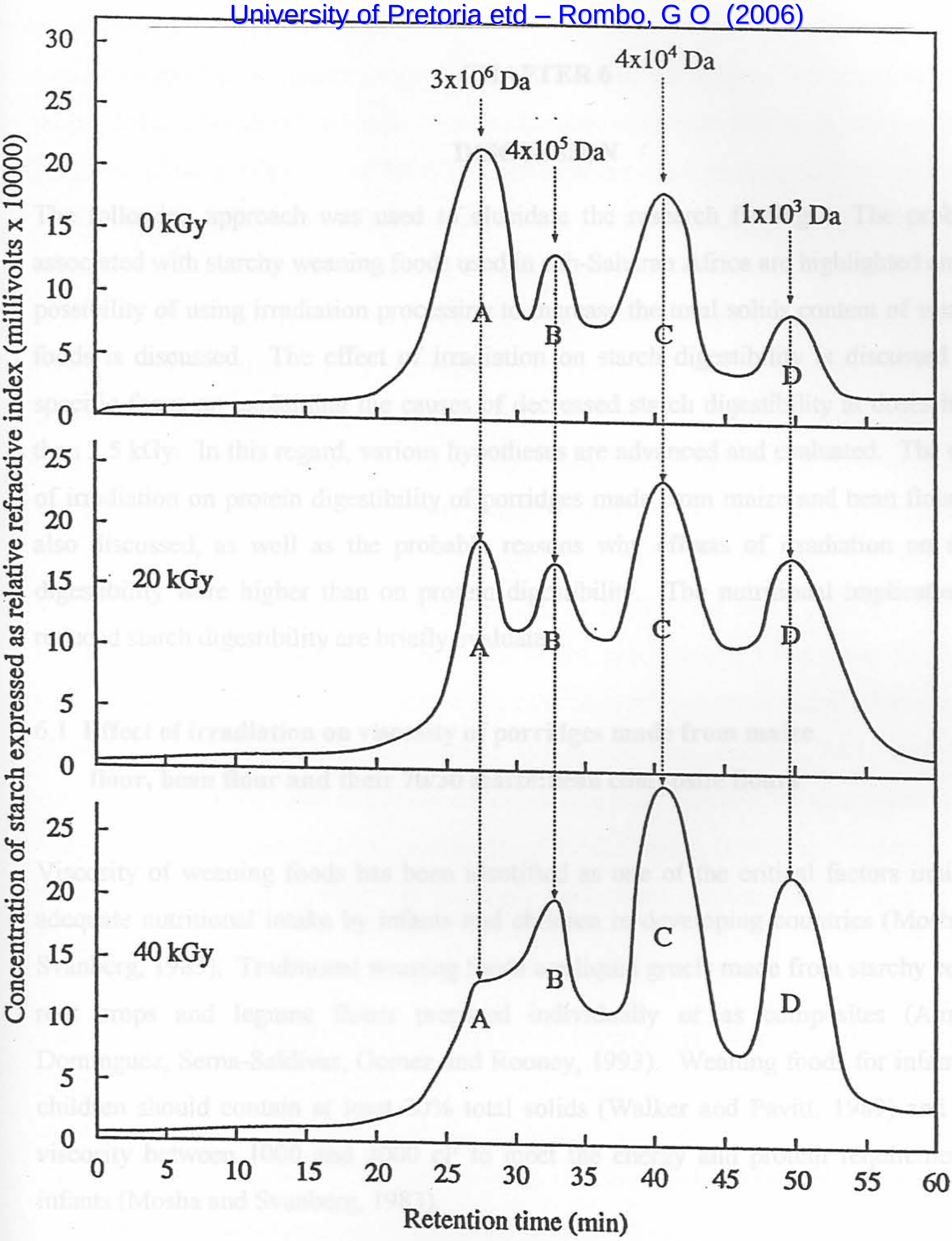

Figure 24 **Effect of irradiation of bean flour on the molecular weight distribution of starch.**