ACAR conductors — a techno-economic evaluation

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USE of aluminium for making electrical conductors is now univeraslly well-established. Large quantities of conductors will be required in India to sustain the rapid pace of electrification and industrialization and this demand has to be almost completely met by aluminium conductors owing to an acute shortage of copper in the country. At present two principal types of conductors viz. AAC (All Aluminium Conductors) and ACSR (Aluminium Conductors Steel Reinforced) are used for overhead transmission lines. The former make use of all strands of 99·5% purity EC grade aluminium metal, whereas in the latter a reinforcement with steel wires is provided to meet the strength requirements of longer spans. Both these types of conductors require EC grade aluminium strands for electrical conduction for which an acute shortage exists in the country and it is likely to persist in spite of the rapid and remarkable growth in our aluminium manufacturing capacity. The object of the present paper is to focus attention on a new type of conductor ACAR (Aluminium Conductor Aluminium Alloy Reinforced) which for a given length of the finished conductor, requires much less quantities of EC grade aluminium and the use of the galvanized steel wire is completely eliminated. At present most of the requirements of the steel wire and all the requirements of zinc for galvanizing are met by imports involving considerable drainage of our foreign exchange. The strength in case of the new conductors is provided by aluminium alloy strands and most of the primary commercial aluminium not considered EC grade at present could be used for making the aluminium alloy strands. Besides, being a very useful substitute for most of ACSR applications, the new conductor can also stand on its own owing to the overall range of flexibility in the electrical and mechanical properties and a number of other techno-economical advantages.

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Special properties of ACAR

High strength/weight ratio

There are about 24 different varieties of ACSR conductors manufactured in India at present and covered under I.S.S. 398–1961. The steel content in these conductors varies from 32% by weight for 6/1 ACSR to 40% by weight for 30/7 ACSR conductors. In ACAR conductors which use no steel wires at all, the strength is controlled by selecting the appropriate number of aluminium alloy strands, thereby making the overall conductor lighter in weight by 21% to 26%. From a perusal of Table I it can be seen that the strength/weight ratios of the new ACAR conductors in many cases are actually better than the conventional ACSR conductors. This plays an important part in the design considerations of sag, span and tower size, the sag calculations being generally based on the following relationship:

$$S = \frac{WL^2}{8H}$$

$$L = \sqrt{\frac{8HS}{W}}$$

where

S = Sag in meters

W = Weight in kg/meter length

L = Length of span in meters

H = Horizontal tension in conductors in kg

Thus, for a specific value of sag (S) with a better strength/weight ratio (H/W), it may be possible to increase the length of the span by 2 to 15% and con-

TABLE I Data sheet, metric system: ACSR, ACAR, and AAAC conductors

		Electrical characteristics					Mechanical characteristics					
					Approx. current carrying capacity							
Code word	Type	Nominal copper area sq. mm.	Equivalent area of aluminium sq. mm.	Resistance at 20°C Ohms/km	at 40°C ambient temp. amps.	at 45°C ambient temps. amps.	Number of wires used	Dia. of wires mm.	Dia. of conductors mm.	Approx. Wt. of conductors kg/km	Approx. U.T.S. of (Breaking load) cond. kg	Strength/(Weight/m) ratio
Gopher	ACSR	16	25·91	1·098	133	123	6 EC, 1 Steel	2·36	7·08	106	952	8980
	ACAR	17	27·64	1·029	137	128	3 EC, 4 Alloy	2·36	7·08	84	786	9350
	AAAC	16	25·65	1·109	132	123	7 Alloy	2·36	7·08	84	977	11630
Ferret	ACSR	25	41·87	0·6795	181	168	6 EC, 1 Steel	3·00	9·00	171	1503	8788
	ACAR	27·5	45	0·6323	187	173	3 EC, 4 Alloy	3·00	9·00	135	1256	9093
	AAAC	26	42·14	0·6751	181	168	7 Alloy	3·00	9·00	135	1587	1176
Rabbit	ACSR	30	52·21	0·5449	208	193	6 EC, 1 Steel	3·55	10·05	214	1860	8692
	ACAR	34	56·20	0·5063	216	200	3 EC, 4 Alloy	3·55	10·05	169	1560	9251
	AAAC	32	52·6	0·5304	210	195	7 Alloy	3·55	10·05	169	1978	11740
Mink	ACSR	40	62·32	0·4565	234	217	6 EC, 1 Steel	3·66	10·98	255	2207	8654
	ACAR	41	66·54	0·4276	242	223	3 EC, 4 Alloy	3·66	10·98	200	1855	9275
	AAAC	39	62·7	0·4537	235	217	7 Alloy	3·66	10·98	200	2360	11800
Beaver	ACSR	45	74·07	0·3841	261	242	5 EC, 1 Steel	3·99	11·97	303	2613	8624
	ACAR	49	79.64	0·3573	271	251	3 EC, 4 Alloy	3·99	11·97	239	2197	9177
	AAAC	45	74·51	0·3819	262	242	7 Alloy	3·99	11·97	239	2566	10740
Raccoon	ACSR	48	77·83	0·3656	270	250	6 EC. 1 Steel	4·09	12·27	318	2746	8630
	ACAR	51	83·01	0·3427	277	258	3 EC, 4 Alloy	4·09	12·27	251	2233	8900
	AAAC	48	77·05	0·3693	267	248	7 Alloy	4·09	12·27	251	2814	11220
Otter	ACSR	50	82·85	0·3434	281	260	6 EC, 1 Steel	4·22	12·66	339	2923	8622
	ACAR	54	88·35	0·3221	290	269	3 EC, 4 Alloy	4·22	12·66	268	2384	8917
	AAAC	51	83·39	0·3411	282	261	7 Alloy	4·22	12·66	268	3009	11250

TABLE II Ra–c/Rd–c ratios of 6/1 ACSR Conductors

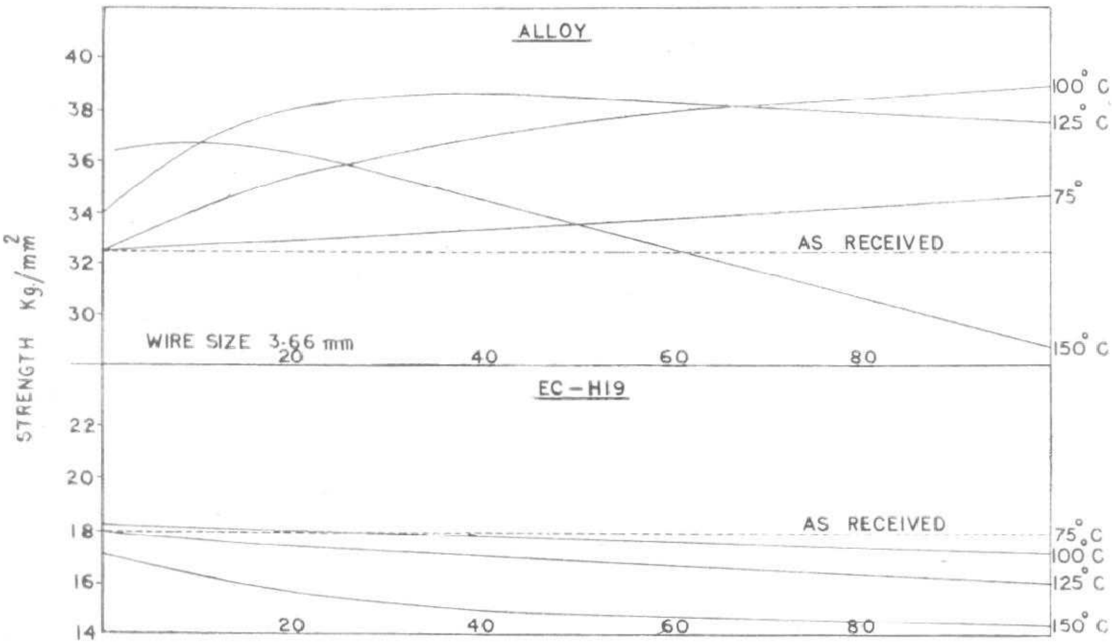
Code word	Conductor diameter mm.	Current Amps.	Resistance at 20°C Ohms/km Rd–c	Ra–c	Ra–c/Rd–c
Cat	13·50	250	0·3020	0·3684	1·22
Cat	13·50	200	0·3020	0·3654	1·21
Otter	12·66	200	0·3434	0·4107	1·196
Raccoon	12·27	250	0·3656	0·4432	1·21
Raccoon	12·27	200	0·3656	0·4324	1·191
Raccoon	12·27	175	0·3656	0·4134	1·135
Beaver	11·97	190	0·3841	0·4301	1·120
Mink	10·98	175	0·4565	0·5088	1·114
Rabbit	10·05	160	0·5449	0·6042	1·109
Ferret	9·00	140	0·6795	0·8504	1·090
Weasel	7·77	120	0·9116	0·9452	1·061
Gopher	7·08	125	1·098	1·14	1·039
Gopher	7·08	100	1·098	1·13	1·029
Gopher	7·08	75	1·098	1·12	1·020
Squirrel	6·33	85	1·374	1·11	1·027

sequently have savings by a proportionate reduction in the number of towers and the associated accessories.

Electrical conductivity

The aluminium alloy strands in ACAR used for imparting strength to the conductors have an electrical conductivity rating of 52·5% IACS in contrast to the extremely low conductivity of the steel wires used in the conventional ACSR conductors. Taking specific design requirements, this could mean from 6 to 11% higher electrical conductivity and better current carrying capacity with lower power losses.

However, the most outstanding advantages of the new ACAR conductors over the conventional ACSR conductors becomes evident only on considerations of the much greater power losses owing to higher a.c. resistance of the latter. The passage of an alternating current through an ACSR conductor magnetises the steel core, the solenoid effect being most pronounced in case of single layer ACSR conductors. The ac/dc resistance ratios in case of single layer ACSR conductors vary between 1·05 and as high as 1·22 (Table II) depending upon the current loading and conductor size as compared to the Rac/Rdc ratio for the ACAR



1 *Strength at elevated temperatures*

conductors being almost unity. Therefore, the simple consideration of d.c. resistance of the two types of conductors (ACSR and ACAR) with the same overall diameters does not present a true picture of power losses. Tables III and IV show approximate order of power losses for Gopher and Raccoon type of conductors, thereby bringing out overwhelmingly the advantages in favour of the new ACAR conductors. Similar calculations can be done in case of other types of conductors as well.

Due to emergency overload and short time fault current effects there may be a rise in the conductor temperature. But the alloy strands of the ACAR conductors actually improve in strength (Fig. 1) under these elevated temperature conditions when the loss in strength of the EC wires due to annealing becomes very pronounced. The allowable temperature limit for ACAR conductors, therefore, is controlled by EC as is the case for ACSR conductors, and is the same as for the corresponding ACSR.

Corrosion resistance

The corrosion resistance of ACAR conductors is much superior to the ACSR conductors owing to the absence of galvanic action between dissimilar metals. This advantage over ACSR becomes particularly very important for severely corrosive areas where even premium priced galvanised steel wires with heavier zinc coating used to improve the corrosion resistance of ACSR does not provide as satisfactory a service.

Light weight construction

Being lighter in weight by about 21% to 26% than the corresponding ACSR the freight and handling cost of ACAR conductors are reduced and their installation becomes easier. The lighter weight also becomes an important consideration in the maximum conductor lengths and number of reel setups frequently having a major influence on the line construction costs. The possible length of ACSR conductors is determined by the length of the unwelded steel core wire which limits the length of conductor. In ACAR, the limit is the size of the bobbin of the stranding machine and exceptionally long conductor lengths similar to EC strands can be fabricated. The longer lengths result in fewer joints with a proportionate reduction in construction time and material economy. The hardness of the alloy wire is about double of the EC wires, thereby making them substantially more resistant to cold flow or creep under compressive stresses as well as to surface scratched in manufacture, shipment and handling. Abrasion resistance of the aluminium alloy strand is over four times that of EC grade aluminium.

Economics of ACAR conductors

In matters of substitution, only technical reasons seldom determine the selection of an alternative material. In this case for the design of a transmission line for a particular service, the overall economic factors incorporating the capital and operating costs have to be considered along with the technical advantages of strength, conductivity,

TABLE III Comparison of power losses for Gopher type ACSR, ACAR and AAAC conductors

Hours	% of Peak load	Line current I_L Amps.	I^2_L	6/1 ACSR 50 cps ac resistance R_{ac} ohms/km.	I^2_L R Watts	3/4 ACAR 50 cps ac resistance R_{ac} ohms/km.	I^2_L R Watts	AAAC 50 cps as resistance R_{ac} ohms/km.	I^2_L R Watts
01	25	30	900	1·098	990	1·029	920	1·109	1000
02	20	25	625	1·098	690	1·029	640	1·109	690
03	20	25	625	1·098	690	1·029	640	1·109	690
04	20	25	625	1·098	690	1·029	640	1·109	690
05	20	25	623	1·098	690	1·029	640	1·109	690
06	40	50	2500	1·11	2780	1·029	2570	1·109	2770
07	40	50	2500	1·11	2780	1·029	2570	1·109	2770
08	50	60	3600	1·11	4000	1·029	3710	1·109	3990
09	50	60	3600	1·11	4000	1·029	3710	1·109	3990
10	60	75	5625	1·12	6300	1·029	5790	1·109	6230
11	60	75	5625	1·12	6300	1·029	5790	1·109	6230
12	60	75	5625	1·12	6300	1·029	5790	1·109	6230
13	60	75	5625	1·12	6300	1·029	5790	1·109	6230
14	60	75	5625	1·12	6300	1·029	5790	1·109	6230
15	60	75	5625	1·12	6300	1·029	5790	1·109	6230
16	60	75	5625	1·12	6300	1·029	5790	1·109	6230
17	80	100	10000	1·14	11400	1·029	10290	1·109	11090
18	100	125	15625	1·16	18130	1·029	16080	1·109	17330
19	100	125	15625	1·16	18130	1·029	16080	1·109	17330
20	100	125	15625	1·16	18130	1·029	16080	1·109	17530
21	80	100	10000	1·14	11400	1·029	10290	1·109	11090
22	80	100	10000	1·14	11400	1·029	10290	1·109	11090
23	60	75	5625	1·12	6300	1·029	5790	1·109	6230
24	40	50	2300	1·11	2780	1·029	2570	1·109	2720
Daily power losses (24 hrs) in watts hour=					159080		144040		152140

weight and other properties. An attempt has been made below to make an economic evaluation of the major factors involved :

Capital costs

Total capital cost for a transmission line may be broadly subdivided into :

(a) Cost of conductors
(b) Cost of transmission towers, accessories and fittings, and
(c) the indirect costs of transportation and installation.

Capital cost

(a) Cost of production

Owing to the added cost of alloying, wire drawing at somewhat slower speeds and finally artificial ageing of the alloy wires to attain optimum properties, the cost of manufacture of the new ACAR conductors may be higher by about 10 to 20% depending upon the type of conductor selected. However, a suitable reduction in manufacturing costs may be achieved by undertaking the manufacture of aluminium alloy redraw rods by well developed and efficient process like the continuous Casting and Rolling Properzi process or rolling of wire bars to get redraw rods. The marginal higher cost of manufacture has to be considered against various advantages accruing on account of lighter weight, better electrical properties and corrosion resistance with the associated advantages of lower handling and freight costs as well as easier installation. Although the initial cost of the conductor may at first glance look more owing to the higher cost of manufacture, this alone obviously cannot be the sole criterion in the final economics of selection.

For the manufacture of ACAR conductors, the same equipments can be used as for ACSR ; only additional equipment required being a heat treating furnace for

TABLE IV Comparison of power losses for Raccoon type ACSR, ACAR and AAAC couductors

Hours	% of	Line current I_L Amps.	I^2_L	6/1 ACSR 50 cps ac resistance Rac ohms/km.	I^2_L R Watts	3/4 ACAR 50 cps nc resistance Rac ohms/km	I^2_L R Watts	AAA 50 cps ac resistance Rac ohms/km.	I^2_L R Watts
01	25	60	3600	0·3710	1340	0·3495	1260	0·3765	1360
02	20	50	2500	0·3710	930	0·3495	870	0·3765	930
03	20	50	2500	0·3710	930	0·3495	870	0·3765	930
04	20	50	2500	0·3710	930	0·3495	870	0·3765	930
05	20	50	2500	0·3710	930	0·3495	870	0·3765	930
06	40	100	10000	0·3765	3770	0·3495	3500	0·3765	3770
07	40	100	10000	0·3765	3770	0·3495	3500	0·3765	3710
08	50	130	16900	0·3875	6550	0·3495	5910	0·3765	6470
09	50	130	16900	0·3875	6550	0·3495	5910	0·3765	6410
10	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
11	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
12	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
13	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
14	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
15	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
16	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
17	80	200	40000	0·4121	16580	0·3495	13980	0·3765	15060
18	100	250	62500	0·4272	27710	0·3495	21850	0·3765	23720
19	100	250	62500	0·4272	27710	0·3495	21850	0·3765	23720
20	100	250	62500	0·4272	27710	0·3495	21850	0·3765	23720
21	80	200	40000	0·4121	16580	0·3495	13980	0·3765	15060
22	80	200	40000	0·4121	16580	0·3495	13980	0·3765	15060
23	60	150	22500	0·3912	8910	0·3495	7860	0·3765	8470
24	40	100	10000	0·3765	3770	0·3495	3500	0·3765	3770
Daily power losses (24 hrs) in watts hour=					233620	0·3495	197430	0·3765	213310

the artificial age hardening of the aluminium alloy wires, to obtain optimum electrical and mechanical properties.

(b) Cost of transmission towers, accessories of fittings

These generally account for 50% of the capital cost. On account of a better strength/weight ratio, it may be possible to increase the length of span while still maintaining the ground clearance as required by Indian Electricity Rules. This may reduce the number of towers by 2 to 15% along with a proportionate reduction in the cost of accessories and fittings. Economy may result from greater conductor lengths and a reduction in the number of reel set-ups and joints.

(c) Cost of transportation and installation

It is difficult to make a quantitative assessment of the savings accruing from the lower freight and handling costs as well as the easier installation in case of the lighter ACAR because of a number of variables involved, the proportion of the savings in indirect costs being much greater in distant and hilly areas. These savings along with those made in the cost of transmission towers, accessories and fittings mentioned in (b) may alone meet the higher cost of manufacturing the ACAR conductors mentioned in (a).

Operating costs

On considerations of operating costs mainly consisting of power losses (I^2R), the economic advantages become overwhelmingly in favour of new ACAR conductors. In case of ACAR conductors the ratio of ac/dc resistance is essentially unity at practically all load currents, whereas in case of ACSR conductors this ratio may become as high as 1·22 (Table II) owing to the magnetisation of the steel core wire. The consequence of an increase in ac resistance is a corresponding increase in conductor losses analogous to the effect

TABLE V Capitalization of the power losses of ACSR, ACAR and AAAC conductors

	Gopher			Raccoon		
	6/1 ACSR	3/4 ACAR	AAAC	6/1 ACSR	3/4 ACAR	AAAC
1. Daily power loss in KWH/km. (on the basis of Table Nos. 3 and 4).	159·1	144·0	152·1	233·6	197·4	213·3
2. Annual power loss in KWH/km.	58080	52570	55510	85270	72090	77780
3. Saving in annual power loss as compared to ACSR in KWH/km.	—	5510	2570	—	13210	7490
4. Cost of saving in annual power loss as compared to ACSR Rs/km. length of conductor (at the rate of 5 paise/KWH).	—	276	129	—	660	375

TABLE VI Evaluation of line voltage drop

Percentage drop in voltage $= \dfrac{\text{kVA}\,(R \cos\theta + X \sin\theta)}{10\text{kV}^2}$

where:

kVA = 3 Phase kVA $= \sqrt{3} \times 4 \times 260 = 1802$

R = Resistance per conductor Ohms/km

X = Reactance per conductor Ohms/km

θ = Power factor angle

kV = Line to line voltage kilo volts = 4

Percentage drop in voltage for 12·66 mm. Cat 6/1 ACSR conductor $= \dfrac{1802(0{\cdot}3620 \times 0{\cdot}8 + 0{\cdot}3419 \times 0{\cdot}6)}{10 \times 4^2}$

$= 5{\cdot}6\%$

Percentage drop in voltage 12·66 mm. 3/4 ACAR conductor $= \dfrac{1802(0{\cdot}2760 \times 0{\cdot}8 + 0{\cdot}3134 \times 0{\cdot}6)}{10 \times 4^2}$

$= 4{\cdot}6\%$.

produced by an increase in a revenue paying load. Thus, extra generating capacity has to be provided to accommodate the higher power losses of ACSR conductors. Although there are many methods for evaluating the true cost of losses, no two methods are in exact agreement. An approximate capitalisation of the power losses for the Gopher and Raccoon type of conductors at a power rate of 5 paise/KWH is given in Table V.

It can thus be seen that only the savings in I^2R losses alone would pay for the entire cost of new conductors in a period of about 2 years. Another saving derived from the substitution by ACAR conductors would accrue from a reduction in line voltage drop, being only 80% of the corresponding ACSR conductors. A somewhat simplified evaluation of this is given in Table VI. There will thus be a reduction in the requirements of such voltage support equipments as capacitors or leading synchronous generators.

Other economic considerations

While considering the overall economics the salvage value of conductors when it has reached the end of its useful life cannot be overlooked. The steel in the ACSR always results in a lower scrap price. The scrap value of ACAR consisting of EC and the aluminium alloy strand is almost the same as EC grade metal.

Conclusion

From a discussion of the various technical and economical factors the new ACAR conductors offer a remarkable range of flexibility to meet specific design requirements. In addition to being very suitable for substituting the conventional ACSR conductors which make a heavy demand on the scarce EC grade aluminium metal, the new conductors offer many benefits for a wide range of applications. It is not claimed that the new conductors will meet the requirements of all applications. There are some applications where the use of steel reinforced conductors may be unavoidable to meet the high strength requirements. However, there is a very wide area of usage where the new conductor can be used with advantage both as a substitute for the conventional ACSR conductors and on its own for a wide variety of applications. The technical and economic advantages envisage a promising future.

Acknowledgement

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Discussions

Mr **P. K. Munshi** (R.D.S.C. Chittaranjan): I would like to know if fatigue, creep, low and high temperature impact properties of Al-alloys have also been studied. If so how do these properties compare with those of structural steel?

Dr **Dharmendra Kumar** (Author): Data are available on various Al-alloys. At low temperatures all these properties actually improve and it is for this reason that Al-alloys are extensively and preferably used for the storage and transportation of industrial gases in liquid state. Above 450°F Al-alloys are not very suitable and the selection of the alloy has got to be made keeping in view the particular end use. Obviously an act of substitution cannot be universal; each application has to be studied separately and designs made according to specific requirements.

Mr **L. J. Balasundaram** (NML): Regarding ACAR conductors will the author clarify how electrical behaviour is influenced especially at high voltage transmission and when skin effect is present?

Dr **Kumar** (Author): Due to the magnetization of the steel core in ACSR there is an increase in the A.C. resistance, which is normally determined experimentally or extrapolated from curves because it does not lend itself to easy mathematical derivation. Now in this respect the new conductor ACAR is quite superior to ACSR because this magnetization does not occur. In ACAR, the A.C. to D.C. resistance is very near unity as compared to the value 1·22 in ACSR. This results in substantial saving in operating costs because of lower power losses.

I may further add that references have been made in the paper to 3 different types of conductors: The ACSR characterised by steel reinforcement is conventionally used in India; in the ACAR, instead of steel reinforcement we are using a few Ec grade aluminium strands and also aluminium alloy strands to impart strength; the third type of conductor is represented by Almalec in which all the strands are of Al-alloy. What we have presented in our paper is therefore a conductor which is based on partial use of Ec grade strands and Al-alloy strands to impart strength.

Mr **Padmanabhan** (TISCO, Jamshedpur): Are ACAR conductors being manufactured now in India or are they still in a development stage?

Dr **D. Kumar** (Author): All aluminium conductors have been in use in France, UK and USA for the last 10 to 15 years but ACAR has come into use in the USA only three years ago. No firm in India has so far undertaken the manufacture of ACAR because the ISI has not yet accepted it and as such there would be no market for the product. In fact the ISI is considering this matter and once it is approved there should be no difficulty whatsoever in starting production.